AD NUMBER
AD910249
NEW LIMITATION CHANGE
TO Approved for public release, distribution unlimited
FROM Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; 01 APR 1973. Other requests shall be referred to Office of Naval Research, Arlington, VA 22203.
AUTHORITY
ONR ltr 14 Dec 1972

COLUMBIA RESEARCH CORPORATION

"DISTRIBUTION LIMITED TO U.S. GOVERNMENT AGENCIES ONLY: TEST AND EVALUATION - 1 APRIL 1973. OTHER REQUESTS FOR THIS DOCUMENT MUST BE REFERRED TO THE OFFICE OF NAVAL RESEARCH (CODE 462.)"

Arlington, Va. 22217

POST OFFICE BOX 485
GAITHERSBURG, MD. 20760

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) COLUMBIA RESEARCH CORPORATION	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
	2b. GROUP —

3. REPORT TITLE

THE F-4 AND THE F-14

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

FINAL REPORT

5. AUTHOR(S) (First name, middle initial, last name)

George C. Sponsler
Dominique Gignoux
Eugene Dare
Norman N. Rubin

6. REPORT DATE May 1973	7a. TOTAL NO. OF PAGES 83	7b. NO. OF REFS 67
8a. CONTRACT OR GRANT NO. N00014-72-C-0339	9a. ORIGINATOR'S REPORT NUMBER(S) 118.3	
b. PROJECT NO. RF018-96-01		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) NONE	
d. NR364-082		

10. DISTRIBUTION STATEMENT

Distribution limited to U.S. Government agencies only: Test & evaluation--1 April 1973. Other requests for this document must be referred to the office of Naval Research (Code 462).

11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Naval Analysis Programs (Code 462) Office of Naval Research Arlington, VA 22217

13. ABSTRACT

Using the F-4 and F-14 as case studies, recommendations for controlling the cost growth of such major weapon systems are developed employing three methodologies: historical analysis; regression analysis; and a novel extension of the classic Lanchester equation.

The principal conclusions are:

1. The F-14 is markedly superior to the F-4 aerodynamically.
2. Fighter aircraft costs have grown at an average 13% annual rate, 3% of which reflects inflation, and the remaining 10% represents increased technical sophistication.
3. The high F-14 cost is still in line with the historic costs of fighter aircraft.
4. The $16.8 million F-14 program unit-cost primarily reflects its multiple-mission capability and abbreviated production.
5. Grumman's last-minute $474 million F-14 bid reduction was probably a buy-in, and is responsible for GAC's subsequent financial difficulties.
6. The GAO finds an average 30% R&D cost growth in major weapons systems; the F-4 was 25% and the F-14, 28%. Low initial R&D estimates are primarily responsible for such cost growth.

The principal recommendations are:

1. Limited-mission fighters and remotely piloted vehicles should be evaluated as the next generation military aircraft.
2. Navy bid-review teams should combine technical, financial, and management experts in one unified body charged to identify probable buy-ins.
3. Strict sanctions, based on parametric projections, should be instituted to force more realistic initial cost estimates.
4. Contracted dollar-payments should reflect actual inflation.
5. The F-14 designation should be changed to FM-14.
6. DoD should consider replacing the F-15 by the F-14.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aerial Warfare: expansion of Lanchester equations						
Aircraft Procurement: criteria for						
Aircraft Armament, its effect on Figures of Merit						
Fighters: procurement evaluation						

COLUMBIA RESEARCH CORPORATION
POST OFFICE BOX 485
GAITHERSBURG, MD. 20760

(301) 948-2450

THE F-4 AND THE F-14 (U)

by:

G.C. SPONSLER OF INTERNATIONAL PLANNING MANAGEMENT CORPORATION
N. RUBIN, D. GIGNOUX, AND E. DARE OF
COLUMBIA RESEARCH CORPORATION

WORK SPONSORED BY NAVAL ANALYSIS PROGRAM DIVISION
OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY

PRINCIPAL INVESTIGATOR: GEORGE C. SPONSLER

CONTRACT #N00014-72-C-0339

TASK #NR364-082

May 1973

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

This report compares the F-14 with its predecessor, the F-4, and draws lessons which would guide the Navy in its future air superiority and fleet air defense fighter design and procurement. The work was conducted under ONR Contract No. N00014-72-C-0339, which called for the development of methods for the "analysis of the effect of technological changes in the development process for major new weapon systems, utilizing the technology, cost, and time histories of the F-4 and F-14 aircraft programs as case studies." Three such methodologies have been identified: historical analysis involving audits of the F-4 and F-14 programs; parametric or regression analysis relating historical fighter aircraft costs as a function of production year and performance factors; and a cost-performance extension of the classic Lanchester equation. As requested by the ONR Scientific Officer, work to date has focused on the historical analysis, the results of which -- augmented by the parametric and Lanchester analyses -- constitute the bulk of the report.

This Executive Summary presents primary conclusions and recommendations which draw upon the findings and analyses presented in the main body of the report. The conclusions are numbered consecutively, with individually related recommendations noted by decimal additions.

1.0 Aerodynamically, the F-14 is markedly superior to the F-4: it is faster, more maneuverable, has greater acceleration, and longer range. These advantages were gained through three principal technical advances: greater use of titanium, providing improved structural strength-to-weight ratios; new gas turbine turbofan power plants, offering significantly higher thrust-to-weight ratios and lower cruise fuel consumption; and the variable geometry wing, augmented by automatic sweep programming, maneuvering slats and flaps, and glove vanes. Technical advances such as these account for the need for -- and the increased cost of -- the development of successive generations of fighter aircraft. The next generation may be special-purpose remotely piloted vehicles, (RPV's), or yet higher speed or single-purpose manned fighters.

1.1 In its future fighter aircraft R&D programs, the Navy should give priority to developments permitting remote control, higher speed, and limited-mission capability. Particular emphasis should be near Mach 3 and above, especially for missiles and RPV's.

2.0 Cost-performance comparisons of the F-4 and F-14 are complicated by the need for common year dollar values and the unavailability of certain F-4 data due to the passage of time. Nevertheless, regression analysis, and particularly application of the new extension to the classic Lanchester equation, offer hope for such comparison. Analysis demonstrates that fighter airplane unit costs have grown at an average 13% per year since World War I. Three percent of that growth may be attributed to inflation. The remaining 10% reflects increasing technical complexity and sophistication. Military cost-control deficiencies could also contribute to that growth; but the fact that the cost ratio between successive generations of military and commercial aircraft has remained the same implies that technical factors predominate.

2.1 The Navy and Congress should anticipate an average annual R&D and procurement cost-growth of about 13% between successive generations of fighter aircraft. Only rates of growth considerably in excess of 13% should be cause for alarm.

2.2 Investigation should be initiated to separate technical growth from lack of cost-control as contributing causes for the corresponding 10% annual cost growth. Appropriate cost-control procedures should then be instituted to limit the cost growth to that caused by technical factors alone.

3.0 The $16.8 million program unit cost of the F-14 -- although not out of line with the historical costs of fighter aircraft -- makes it the most expensive general purpose fighter airplane in the world (with the exception of the limited-production, special purpose A-11). If the Navy and Grumman were to renegotiate the present contract, that cost could increase to $18.6 million, or even more, depending on the final terms. The primary causes for this high unit cost (a much higher cost than that of the F-4) are the F-14's extreme multiple-mission capability, and its reduced production run of only 313 airplanes. This high unit cost, particularly in the light cast by the 13% historical annual cost growth, probably marks the F-14 as the end of the era of costly, multi-purpose heavy jet fighter aircraft. Indeed, the F-14/Phoenix/AWG-9 system probably represents a transition between the present era and a future new era of remotely manned vehicles, since the Phoenix, in a sense, is such a vehicle.

3.1 The Navy should carefully evaluate the real and supposed benefits of future multiple-mission fighter aircraft. Single-purpose aircraft may permit considerable cost savings.

3.2 As part of this review, the Navy should undertake a deeper study of the next generation fighter airplane requirements, and investigate the possibility that they could be met by remotely manned vehicles or other approaches -- such as the lightweight fighter -- permitting substantially reduced weapon system unit costs.

4.0 The last-minute $474 million reduction in the original Grumman Aircraft Corporation bid during the F-14 competition constituted a buy-in, in our opinion, and is primarily responsible for the current financial difficulties experienced by Grumman Aircraft Corporation with its F-14 contract.

4.1 The Navy should make better use of its own parametric cost estimates as guides for contractor selection and weapon system costing. Navy negotiators should be made responsible for identifying possible buy-ins They should replace their former policy of procuring the most favorable terms for the Government, regardless of circumstances, by a policy of emphasizing good judgement as to price realism and equitable terms of contract. The Navy team should combine technical, contracting, and management experts into <u>one joint</u> team who work together rather than as separate entities, as at present. This combined group would determine whether contractors' bids constituted buy-ins or contained built-in cost overruns.

5.0 Historically, the General Accounting Office has found that all major weapon systems have shown an average cost growth of 30% over the initial estimates. The F-4 experienced a 25% overrun in the R&D phase, and the F-14, 28%. Low initial R&D estimates are primarily responsible for such cost growth.

> 5.1 To enforce more realistic future estimates, Congress and the Navy should impose appropriate sanctions -- such as disqualification for future awards, loss of profit, dismissal, or demotion -- upon contractor and Defense Department executives who are responsible for proposing and accepting initial cost estimates of winning contracts which subsequently demonstrate unacceptably large overruns as defined by a priori parametric estimates.

6.0 The Congress shares responsibility for helping to create the conditions which foster buy-ins and low estimates. The often extreme budgetary pressures exerted by Congress directly influence both the military and its contractors to adopt overly optimistic estimates of probable costs. Independent and repeated Senate and House committee appropriation hearings are also duplicative, time-consuming, and may contribute to cost growth through schedule disruption.

> 6.1 The Congress should institute its own program analysis staff to develop appropriate parametric projections, and otherwise to assist the Congress in determining reasonable costs of future weapon systems.

> 6.2 Joint hearings should be held by the relevant Senate and House committees for the purpose of receiving information from DoD witnesses during annual program and appropriation reviews.

> 6.3 Where appropriate, the Congress should institute more continuing multi-year funding of selected major weapon systems development programs.

7.0 Grumman Aircraft Corporation attributes its F-14 cost growth to three factors: inflation, accounting for 28% of the total growth; increased overhead charges due to business base erosion, 40%; and contractor initiated engineering changes, 32%. Recognizing the contractor initiated engineering changes as reflecting solutions to unforeseen technical problems such as are frequently encountered in the research and development of major weapon systems, the following three recommendations should be helpful in containing future cost growth of major weapon systems after contract award.

7.1 Incorporation of realistic <u>short-term</u> inflation estimates, as determined by the Government for the duration of the contract and based on the last projection of the Bureau of Labor Statistics, should be mandatory in all future contracts. Better, the actual dollar payments under the contract could be revised automatically in accordance with the actual inflation experienced.

7.2 The Government should never renegotiate contracts because of higher overhead rates resulting from business base erosion. However, if conversion of a contractor-owned facility to a non-defense activity were considered undesirable by the Government, separate contracts could be entered into, which in the form of payment of rent or option to use, would motivate the contractor to keep the facility idle, ready for reactivation.

8.0 The public and Congress have been sensitized by far more dubious weapon programs such as the C-5 and the F-111, and are overreacting to the F-14 problems. The development and production of the F-14 do not show evidence of mismanagement since award of the contract, the plane performs according to specifications, and only the "B" engine development has presented substantial technical problems. Actually, the combination of the F-14, the Phoenix missile, and the AWG-9 constitutes a unique long-range air defense weapon system. In essence, the Phoenix is a remotely piloted vehicle launched by the F-14. A new terminology is required to differentiate such a complex weapon system from relatively simpler fighter aircraft, such as the F-4, employing conventional air-to-air missiles.

8.1 In order to distinguish the unique F-14/Phoenix weapon system, the designation of the F-14 should be changed to F<u>M</u>-14, the "M" reflecting the Phoenix missile capability. This distinction should also help in explaining to Congress and the public the high cost of the combined weapon system, in comparison with more conventional fighter airplanes.

9.0 By extension of the classic Lanchester equation, it can be shown that if two forces of fighter aircraft are of equal fighting strength <u>and</u> of equal cost, then the ratio of the two individual aircraft fighting capabilities must equal the square of their unit costs. Neglecting the cost of the Phoenix missiles themselves, and employing certain other simplifications, the fighting strength of the F-14, represented by its Phoenix missile capability, compensates for its cost differential vis-a-vis the F-4.

9.1 A sophisticated Lanchester equation cost-effectiveness analysis should be undertaken of the F-14/Phoenix/AWG-9 weapon system in contrast with the F-4, which would incorporate the cost of the Phoenix missiles, eliminate the simplifications presently employed, and include measures of effectiveness of the relative aerodynamic capabilities of the two aircraft.

10.0 To fund the cost growth experienced during the R&D phase of the F-14 contract, the Navy effectively transferred funds from production to R&D. This transfer was accomplished by redesignating some half-dozen fighters, previously scheduled as procurement models, as research and development vehicles.

10.1 The Congress should issue appropriate regulations governing the <u>effective</u> transfer of funds from procurement to research and development. The direct transfer of funds should remain illegal, except where exceptions are expressly permitted by act of Congress. Better R&D cost-control should result.

11.0 The smooth development of the F-4 -- in contrast to the F-14 -- was encouraged by the decentralization which then existed within the DoD and the Navy. The management histories of the F-4 and the F-14 support the conclusion of the Commission on Government Procurement that management layering, excessive staff reviews, unnecessary procedures, extensive reporting, and other paperwork are counter-productive in the development of major weapon systems.

> 11.1 Greater management decentralization should be encouraged again within the DoD under future weapon system R&D and procurement procedures. Management layering, staff reviews, reports, and paperwork should all be minimized.

12.0 For the same total production, unit production costs of the F-14 and the F-15 would be approximately the same. Although the F-14 is a larger plane than the F-15, the advantage gained by its swing-wing should make it more maneuverable. The F-15 should have greater acceleration, but the top speeds of both aircraft are limited by the thermal barrier to approximately the same figure. With the exception of the fleet air defense mode employing the Phoenix missile -- which can only be undertaken by the F-14 -- the missions of the F-14 and the F-15 are essentially the same. Indeed, the F-14 would have a certain advantage in that its range and loiter time on station are greater than those of the F-15. From the standpoint of national or Department of Defense economy, the two aircraft would appear to be, to a large measure, duplicative.

> 12.1 Since the F-14 can carry, launch, and control the Phoenix missile, which the F-15 cannot, the DoD should consider replacing the Air Force F-15 with the Navy F-14. The F-14 would thus become a tri-service fighter, as is its predecessor, the F-4. To that possible end, a careful comparison of the two airplanes should be undertaken by the DoD. That comparison should consider the various missions anticipated for the two aircraft, and should include appropriately designed fly-off trials.

II. INTRODUCTION

In contrast with the highly successful F-4, it has been suggested that the history of the F-14 presents a microcosm of the problems confronting the development of modern, highly complex weapon systems. Troubled weapon systems such as the C-5A, or the Main Battle Tank, or the TFX/F-111 fighter aircraft have exhibited three common problems: repeated major technical failures; prolonged schedule slippage; and extravagant cost growth. During its development, the F-14 has exhibited a cost growth of 28%. But the F-4 R&D expenses grew 25%, and the GAO finds an average 30% growth for all major weapon systems. Neither the F-4 nor the F-14 experienced the profound and crippling technical problems which have often confronted and confounded the military in the development of other weapon systems. However, the F-4 tail design caused problems, and the F-14's F-401, or so-called "B", engine has been a continuing problem in development. Also, both the F-4 and the F-14 experienced crashes during their flight tests, but neither has had nearly as many crashes or such technical problems as those of the F-111. The F-14 has performed within specifications, and it is anticipated that it will meet its planned initial operational capability date in the fleet in 1973. Its problem is its unit cost: the F-14 is the most expensive general-purpose fighter ever built.

Critics led by Senator Proxmire assert that the F-14 program cost of $16.8 million per plane is grossly excessive and that the program should therefore be cancelled. Such critics suggest that the F-14 should be replaced by a lightweight, lower cost airplane yet to be designed. One recurrent proposal is that the F-14 should be replaced by an improved version of the F-4. Indeed, the F-14 was designed as the successor to the F-4, to provide fleet air defense and general air superiority capability. The Navy plans to replace its F-4 Phantom II aircraft in the future with F-14 Tomcats, and defends the F-14 strongly against any suggestion that it is not a superior aircraft to the F-4 aerodynamically and as a fighting weapon.

The primary purpose of this report is not to compare the performance of the F-4 and the F-14 -- although aerodynamic factors do enter. Rather, it is our intent to contrast the development histories of the two aircraft in an attempt to determine objectively what technical and economic factors account for the cost growth of the F-14, and to attempt to indicate procedures whereby such cost growth could be controlled in the development of future fighter aircraft. The methodology of this report is therefore primarily historical. Because of the controversial history of the F-14 and the universally gratifying reception of the F-4, tremendous amounts of information are available in the unclassified literature on both aircraft and upon their development histories. (The cost details of the F-4 are more difficult to obtain.) The principal sources of information include: Congressional hearings; certain GAO reports; newspaper and magazine articles; and company promotional material. Of these, it is fair to say that the Congressional hearings have supplied most of the historical information presented hereafter -- with important points of clarification and extension drawn from other sources, including personal interviews with knowledgeable individuals associated with both the F-4 and the F-14 aircraft.

The objective of the overall study was to develop appropriate methodologies which would facilitate the analysis of such complex weapons systems. Quoting from the contract work statement: "The Contractor shall ... develop methods for analysis of the effect of technological changes in the development process for major new weapon systems, utilizing the technology, cost and time histories of the F-4 and F-14 aircraft programs as case studies." As requested by the ONR Scientific Officer, major emphasis has been placed on the historical audits of the F-4 and F-14. However, in addition to historical analysis, parametric or regression cost analysis has been employed; and an entirely new extension of the classic Lanchester equations derived. In the following sections, the development and cost histories of the two aircraft are presented first, followed by a regression analysis of historical fighter airplane costs (emphasizing the effects of inflation and technical sophistication); and finally, a novel cost-effectiveness comparison of the F-4 and the F-14 is presented, based on the application of the Lanchester N^2 Law extension. It is believed that we have succeeded in identifying the principal causes for the cost growth of the F-14. Grumman Aircraft's initial $474 million bid reduction aggravated financial difficulties caused by inflation, eroded business base, and contractor initiated technical changes. And we have discovered what we believe is an appropriate and heretofore unknown cost-effectiveness comparison, which indicates that the Phoenix missile ultimately must justify the F-14 unit cost. Conclusions and recommendations of particular importance are included in the Executive Summary.

III. DESCRIPTIONS OF THE F-4 AND F-14

The F-4 and the F-14 are both air superiority fighter aircraft, originally intended to perform in the fleet air defense role. The F-4 Phantom II is a tri-service military aircraft employed by the Navy, Marine Corps, Air Force, and many foreign nations. The F-14 Tomcat is intended to replace the F-4. The sizes of both aircraft grossly have been dictated by aircraft carrier space limitations such as elevator size, overhead clearance, and flight and hangar deck dimensions. Thus, the original length of the F-4 was established at 56 feet to permit use of the center elevator of certain U.S. aircraft carriers. Subsequently, the nose section of the F-4 was lengthened by 2 feet to accommodate the largest fighter radar antenna currently in use in the free world.

The gross characteristics of the F-4 and the F-14 are presented in Table 3.1. Although the F-4 is a Mach 2 plus aircraft, with speeds in excess of 1,200 miles per hour, the use of leading and trailing edge flaps augmented by boundary layer control allow the F-4 to land more slowly than a commercial jet airliner. The faster F-14 can land even more slowly than the F-4. The combat range of both planes is on the order of 500 miles, although the F-14 has a longer loiter time capability.

There are twelve distinct configurations of the F-4: nine fighters; and three reconnaisance models.

The first fighter model, the F-4A, comprised 47 aircraft, 26 of which were employed as research and development vehicles -- prototypes in a very real sense -- and the remaining 21 were assigned to training squadrons. It was replaced by the F-4B, which was the U.S. fleet's primary air defense interceptor from 1962 until 1967, when it was replaced by the F-4J. The F-4B incorporated the larger radar antenna, longer nose, and more powerful engines. The U.S. Air Force adopted the F-4C as its primary Tactical Air Command aircraft in 1962. Certain changes were introduced to accommodate the different mission requirements of the Air Force, including cartridge air starters, various inertial navigation systems, and incorporation of other

TABLE 3.1

F-4 AND F-14 CHARACTERISTICS

		F-4	F-14
Length Overall (feet and inches)		58' 3"	61' 10.6"
Wingspan:	Extended	38' 5"	66' 1.5"
	Folded or Retracted	27' 6½"	33' 2.5"
Height Overall		16' 3"	16'
Weight:	Empty (lbs.)	~30,000	~36,000
	Maximum Takeoff	~45,000	~53,500
Speed, Maximum (Mach)		~M 2.2	~M 2.4
Combat Ceiling (feet)		~55,000	~60,000

~ = approximately

air-to-ground mission capability aids. A version of the F-4C, known as the F-4D, was developed to yet further improve the air-to-ground mission capability . A lead-computing optical sight weapons-release computer was installed and the radar was modified to include air-to-ground ranging. The F-4D was purchased by the air forces of Korea and Iran. The F-4E, also employed by the U.S. Air Force, incorporated an M-61 Vulcan cannon to complement the long-range Sparrow III and medium-range Falcon missiles. An improved J-79-GE-17 engine was also installed, together with a more reliable radar -- the APQ-120. The F-4E has been purchased by Iran, Japan, Israel, and Australia. The F4F, purchased by the German Air Force, uses the same basic airframe as the F-4E, but is optimized for air superiority by the addition of leading edge maneuvering slats and systems simplifications which permit operation by a single pilot. The F-4J is the current version of the Phantom II employed by the U.S. Navy and Marine Corps. The primary modification was incorporation of the AWG-10 pulse-doppler radar with a look-down capability to permit the detection and tracking of aircraft flying at lower altitudes with radar sea and ground return. The F-4J employs higher thrust J-79 engines, a one-way data link with automatic carrier landing capability, and dropped ailerons and slotted stabilator to reduce landing speeds. Structural changes were also incorporated to permit heavier carrier landing weights. The U.K. Royal Navy purchased the F-4K, an outgrowth of the F4-J, the primary modification being the substitution of the Rolls Royce Spey bypass engine, which provides higher power and longer cruising radius. Structural modifications were also incorporated to permit the installation of the new engines. The F-4M, employed by the Royal Air Force, is essentially the F-4K adapted to primarily land-based operations. Certain carrier suitability features have therefore been removed. In addition, the F-4M is equipped with a long-range voice communications capability.

Reconnaisance versions of the Phantom II include the RF-4C, employed by the U.S. Air Force, in which the forward fuselage section was designed to house the optical electronic sensor equipment needed to perform tactical reconnaisance. The RF-4B is employed by the U.S. Marine Corps with the addition of an inertial navigation capability not found in the F-4B. It is essentially an RF-4C with a higher thrust J79-GE-17 engine. It has been purchased by Germany, Israel, and Iran. The German Luftwaffe has also developed a new longer range side-looking radar version.

The armament of the F-4 incorporates four all-weather radar-guided Sparrow III air-to-air missiles or, alternatively, Falcon short-range missiles, or Sidewinder IR homing missiles, or the M-61 20mm Gatling Gun cannon. The F-4, in an air-to-surface mission, is capable of carrying more than 8 tons of conventional bombs, rockets, missiles, land or sea mines, guns, napalm, or nuclear weapons.

The weapons for the F-14 are the same as those for the F-4, with one major difference -- the Phoenix long-range radar-guided air-to-air missile. Indeed, it was as a platform for the launching of the Phoenix missile that the F-14 was originally designed and intended in its fleet defense role. As will be seen subsequently, in considering the cost-effectiveness of the F-4 and the F-14, the compensation for the increased cost of the F-14 over the F-4 must be supported primarily by the increased effectiveness given the F-14 by the Phoenix missile.

It was the requirement that the F-111B must carry the Phoenix missile, which demanded the extra structural strength, and hence weight, over the Air Force version and which in turn led to the F-111B's inability tooperate from aircraft carriers. It is this same Phoenix requirement, incidentally, which in large measure accounts for the added size and weight of the F-14 when comparing it with the Air Force F-15.

The F-4 has the lowest maintenance man-hours per flight hour required of any current U.S. fighter aircraft. It has established many world and class records for altitude and speed over a closed course, and time to climb to various altitudes. Set in the early 1960's, these records were only beginning to be replaced, primarily by Russian-built aircraft, in the latter 1960's and early 1970's, by planes such as the MIG-23 Foxbat. The F-4 has been the mainstay attack plane for Air Force, Marine, and Navy flyers in Vietnam.

The Grumman F-14 was planned in three versions. The F-14A employs two Pratt and Whitney TF30-P-412 turbofan engines with afterburners, initially developed for the F-111B. The F-14B airframe and avionics are basically those of the F-14A, but it will be powered by two Pratt and Whitney F-401 turbofan engines, giving it considerably augmented performance. Indeed, initially the F-14 was designed primarily for the "B" engine.

The F-14C was planned as a development version of the F-14B incorporating new avionics and weapons, but it is not now currently under development.

Even at the time the F-4 was developed, it was recognized that considerably improved performance could be gained through three technical advances which have been incorporated in the F-14. The first of these is the replacement of more aluminum with titanium, (and, to a lesser extent, boron composites), which reduces structural weight and improves high maneuver "G" limits. The reduced deadweight improves just about every performance parameter, including range, payload, acceleration, characteristics of climb, etc. Only about 9½% of the F-4's structural weight is titanium. The F-14's percentage is greater, being some 25%. The F-4 Phantom II makes effective, if limited, use of titanium primarily in the main structural keel member between the engines and for inner liners for the pressurized engine compartments. Altogether about 900 lbs. of titanium were used in each of the early Phantom II's. Later models increased that use by a factor of two. The F-14 makes far more substantial use of titanium to gain optimum strength-to-weight ratios. It is anticipated that its structural strength and high thrust-to-weight ratio, particularly with the "B" engine, will enable the F-14 to have speeds substantially in excess of Mach 2, with great agility in close-in air-to-air combat.

The second technical improvement of the F-14 over the F-4 is the use of new gas turbine turbofan power plants, which have something on the order of twice the thrust-to-weight ratio and half the specific fuel consumption of the engines originally employed on the F-4. These new engines on the F-14 provide even wider cruising radii for the same total fuel consumption. The "B" engine will give the F-14 an aircraft thrust-to-weight ratio greater than 1, assuring tremendous acceleration, high speed, and even the ability to climb vertically, if required.

The variable-sweep wing is the third -- and most important -- major technical advance of the F-14 over the F-4. It is particularly valuable in a multi-mission plane -- permitting lower landing speeds, higher top speeds, longer loiter time, and a wider cruising radius, corresponding to the variable wing loadings permitted by the various wing settings.

The F-14's wing features probably make it the best air superiority fighter in the world today. The F-4 has enjoyed this title for about 12 years, which is an amazing record in itself. However, the special features of the F-14 have proven that, by design comparison and by actual flight operations, the F-14 emerges as perhaps the best air-superiority fighter in the free world today. Furthermore, almost alone among U.S. fighters, it has the capability (in the fleet air defense mode) of shooting down the MIG-23 (redesignated as the MIG-25 in January 1973) -- a very high altitude and very fast Russian fighter. The Phoenix missile, which is not part of the normal F-14 air-superiority armament, could accomplish this kill at greater range with higher probability than any other free-world fighter.

Grumman's experience with the XF-10F -- the first swing-wing aircraft built in the U.S. -- and the F-111B provided the background of technical experience needed to design several major advantages into the F-14 variable-sweep wing which either do not exist or exist only in minor form in competitive fighters.

The F-14 has three such unusually effective and unique features associated with its variable-sweep wing:

1. Automatic sweep programming;
2. Maneuvering slats and flaps; and
3. Glove vanes.

These three features provide optimum lift-to-drag ratios throughout the entire dog-fight speed zone.

It is generally acknowledged that most dog-fights occur below Mach 0.9; however, there is some feeling that this figure should be raised to Mach 1.2. This upper limit is determined by the pilot's ability to see the enemy fighter after an opposite direction pass (head on) and subsequent 180° turn. At higher speeds, the radius of turn is so great that the operating aircraft lose each other visually after the initial pass.

At the low end of the Mach spectrum (below 0.8), the F-14 maneuver slats and flaps offer a significant increase in lift by decreasing the effective wing loading from 85.6 PSF (pounds per square foot) to 50.6 PSF. This increase in lift is at its maximum with the wing at 22°, the full forward position. The F-14 advantage which cannot be realized in aircraft without variable-sweep wings, is that the 5% chord thickness of the fully swept wing (at 68°) becomes a 9% chord with the wing in the full forward (22°) position, as depicted in Figure 3.1. This "fat" wing, with the associated increased span at full wing extension, gives an excellent coefficient of lift, not available to a competitive fighter without variable sweep, and adequate room for the mechanical installation of the maneuver slats and flaps themselves.

Figure 3.1 shows the "fat" wing in the full forward position and the slat-flap arrangement. It also shows the change in effective chord with the F-14 wings fully extended and retracted.

Figure 3.2 shows the relative turning capability with the slats and flaps both extended and retracted, and a comparison with the F-4 and the MIG-21. These two airplanes, of course, have fixed (not variable) wing angles.

Automatic sweep programming is a dramatic advantage not available to any other known fighter. Going from the maximum F-14 sweep (68°) to the full forward (22°) position, the auto sweep programming modulates the wing to "ride the envelope" or capitalize on the span loading payoff of variable sweep. This advantage is available from Mach 1 to Mach .7, which is where most dog-fights would begin. All pilots agree that this is a feature which definitely would be used and which would materially add to dog-fight superiority.

The curves on Charts 3.3 and 3.4 show how the auto sweep programming improves the air-superiority fighter performance.

Figure 3.3 shows the relative wing efficiency plotted against speed. Fixed sweep angles are shown including the F-4 (approximately 50°) and the MIG-21 (approximately 70°), as well as the optimum curve which the F-14 flies by auto programming its sweep angle with speed.

(Incidentally, the data for Figures 3.2, 3.3, and 3.4 -- and those for the following figures, 3.5, 3.6, and 3.7 as well -- were derived from actual wind-tunnel tests.)

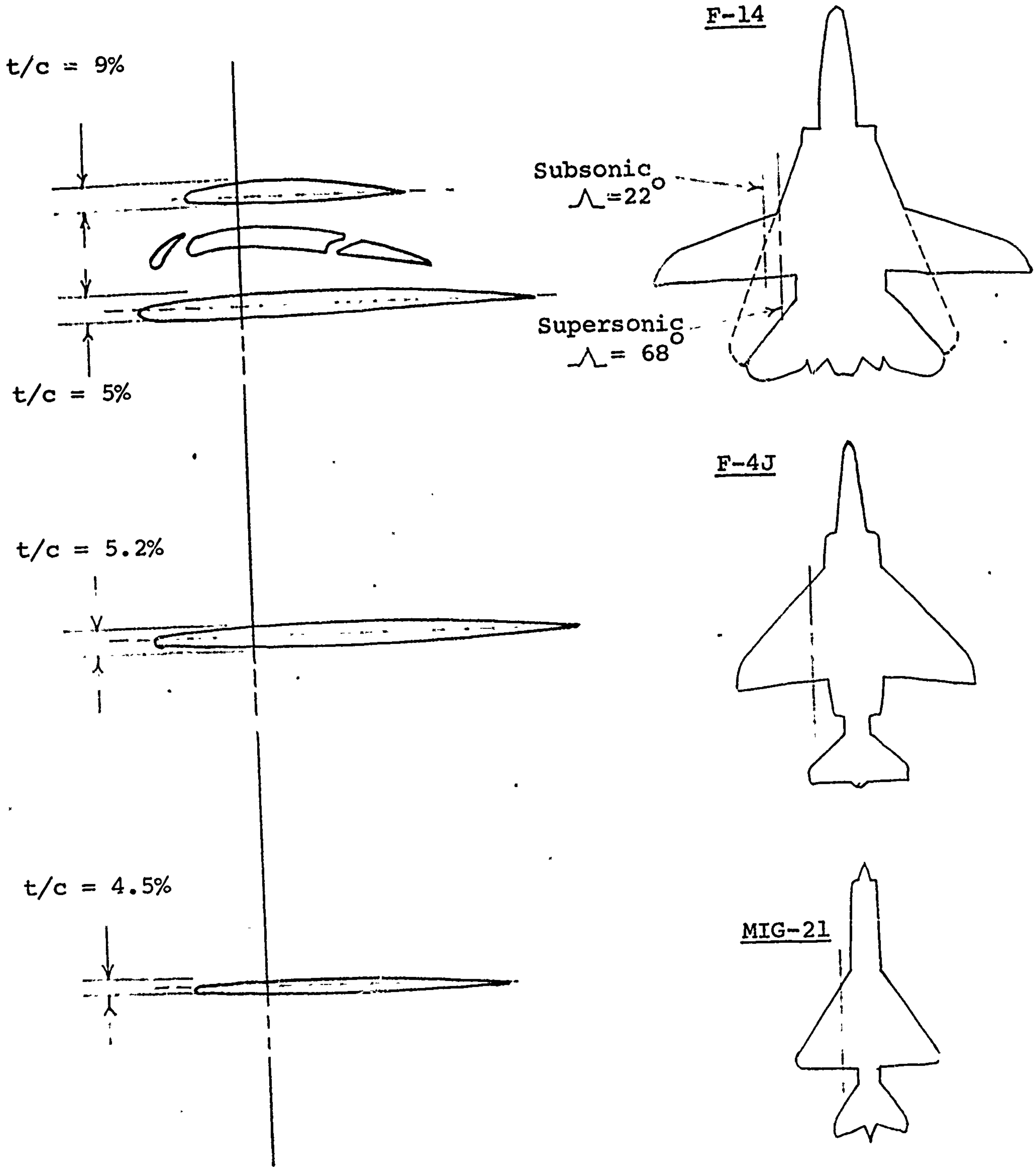


FIGURE 3.1. COMPARISON OF WING THICKNESS TO CHORD (t/c) ON THE F-14, F-4, AND MIG-21

(Source: Grumman Aircraft Corp.)

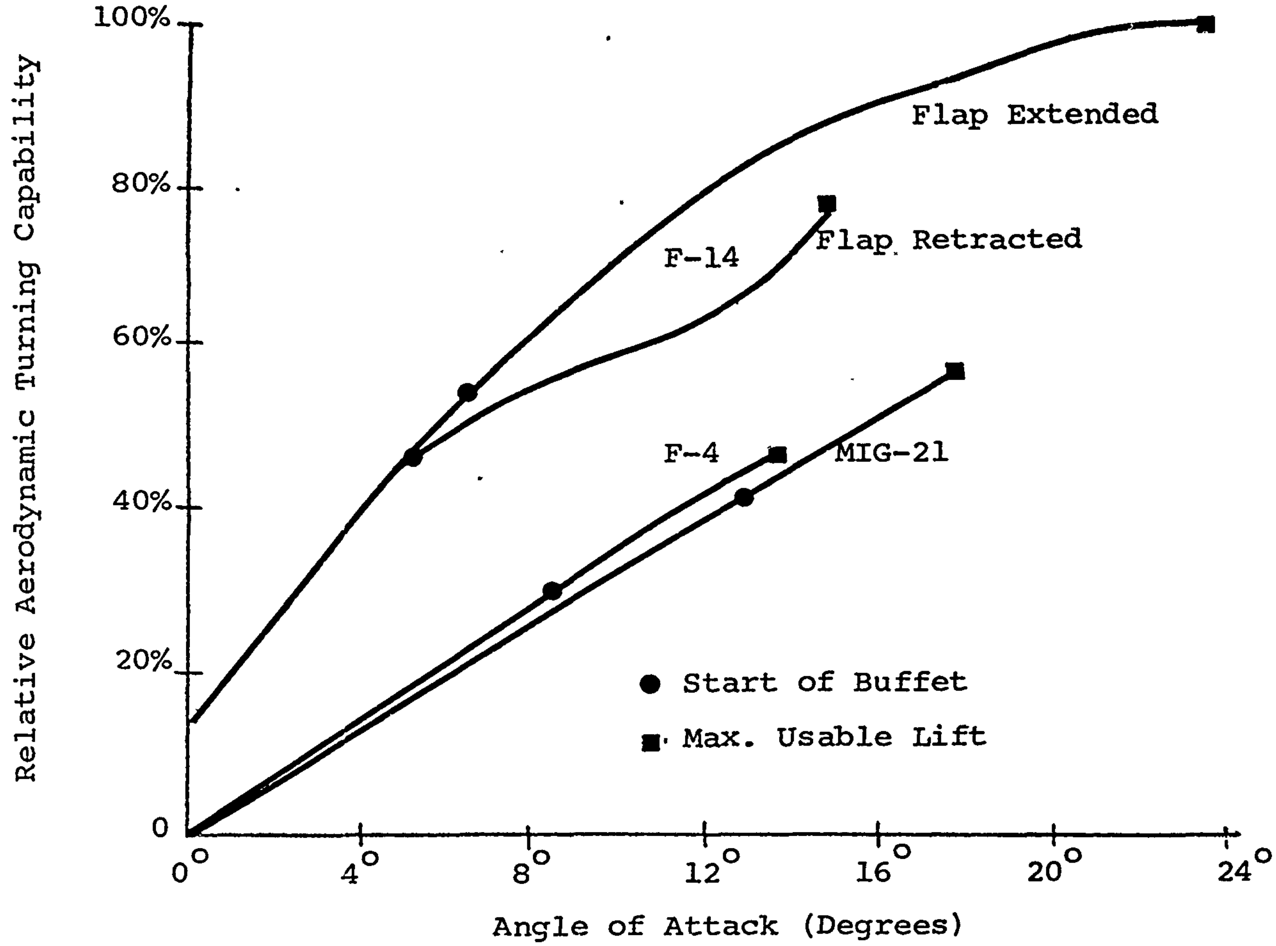


FIGURE 3.2. F-14 MANEUVER SLAT/FLAP LIFT EFFECTS ON TURNING CAPABILITY AS COMPARED TO THE F-4 AND THE MIG-21.

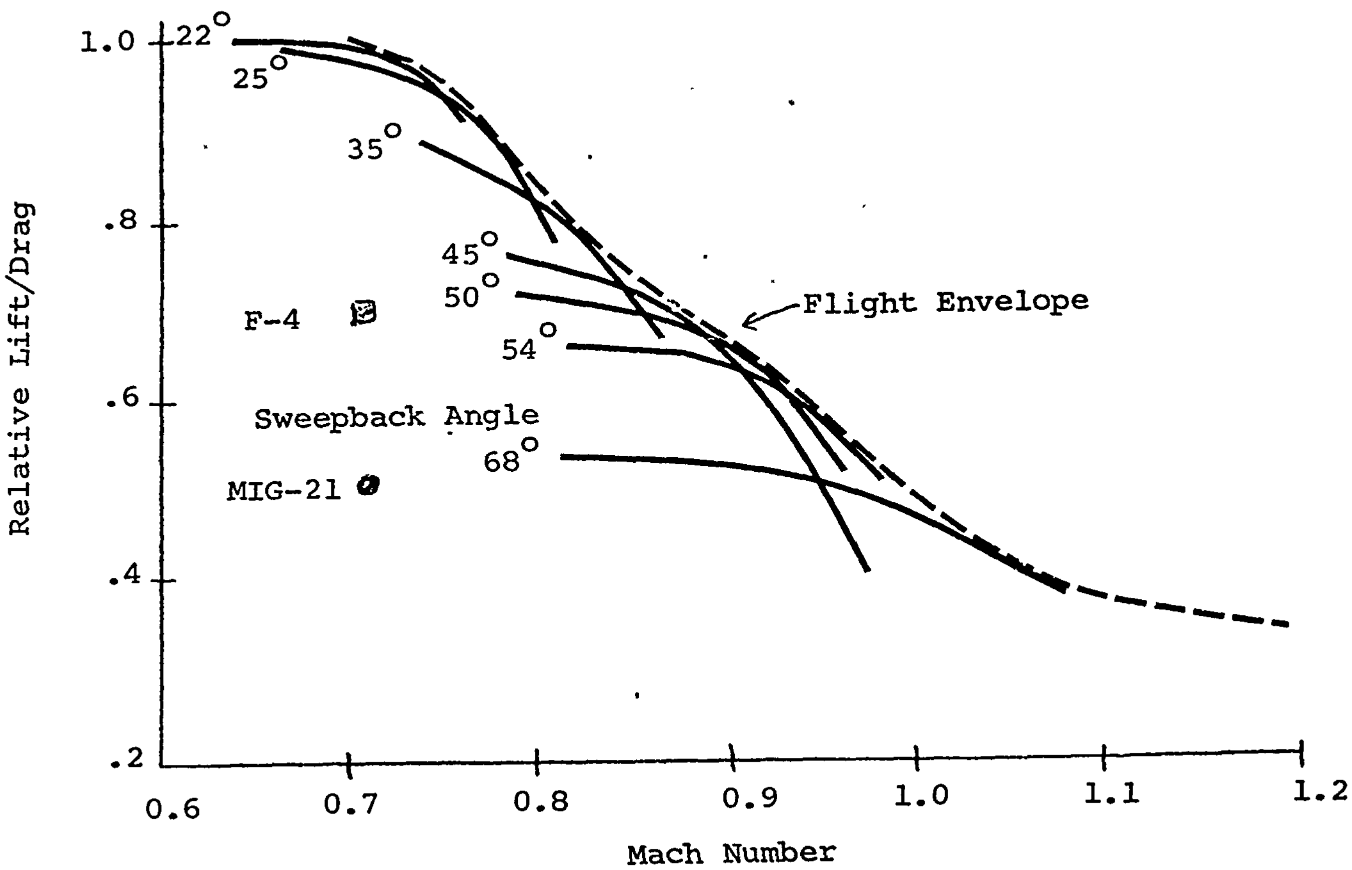


FIGURE 3.3. F-14 FLIGHT ENVELOPE LIFT/DRAG VERSUS SPEED

(Source: Grumman Aircraft Corp.)

Figure 3.4 shows a comparison of a fixed sweep (50°) aircraft such as the F-4 with the F-14 auto sweep program aircraft: first in normal flight (1G), and then in a 4G turn. With the exception of equality at about .9 Mach, the variable sweep has measurable advantage at both the lower speeds (approximately .7 Mach) and the higher speeds (approximately 1.2 Mach).

The F-14 glove vanes are controlled both manually and automatically. Their real value is at supersonic speeds, and their principal advantage is that they reduce the tail load (drag) and hence increase the power (thrust) available. There are several aircraft throughout the world that use canards for the same purposes as the glove vane. But, as far as is known, they are not as effective in allowing the aircraft to achieve maximum lift-over-drag (L/D) at high altitudes; a very real advantage where tight turns at high altitudes and supersonic speeds are required. Curves 3.5 and 3.6 show the advantages of using the glove vanes aerodynamically.

Figure 3.5 shows the maneuvering advantage with the vane extended over the vane retracted. This advantage is expressed as the load factor which can be achieved, plotted against speed. The relative capability of the F-4 is shown for comparison purposes. This figure indicates that the F-14 could perform much tighter turns at altitude than aircraft without the vane, such as the F-4.

Chart 3.6 shows again the same advantage in terms of relative turning capability versus drag.

The automatic control of wing sweep and glove vane is an extremely valuable feature. The only precedent known to the authors where some similar function was accomplished automatically is the Kawanishi N1K2-J (Shiden - KAI) of World War II. A unique design feature of this Japanese fighter was Wing Flaps operated automatically to increase lift when necessary during extreme maneuvers. The device operated with an electric and pneumatic control using a U-shaped tube containing mercury. This was then recognized as an important factor in the aircraft maneuverability in combat.

In any new aircraft such as the F-14, there are numerous advances which incorporate the experience of its designers, builders, operators, pilots, etc. The wing advantages dicussed heretofore are, in addition to other major technological improve-

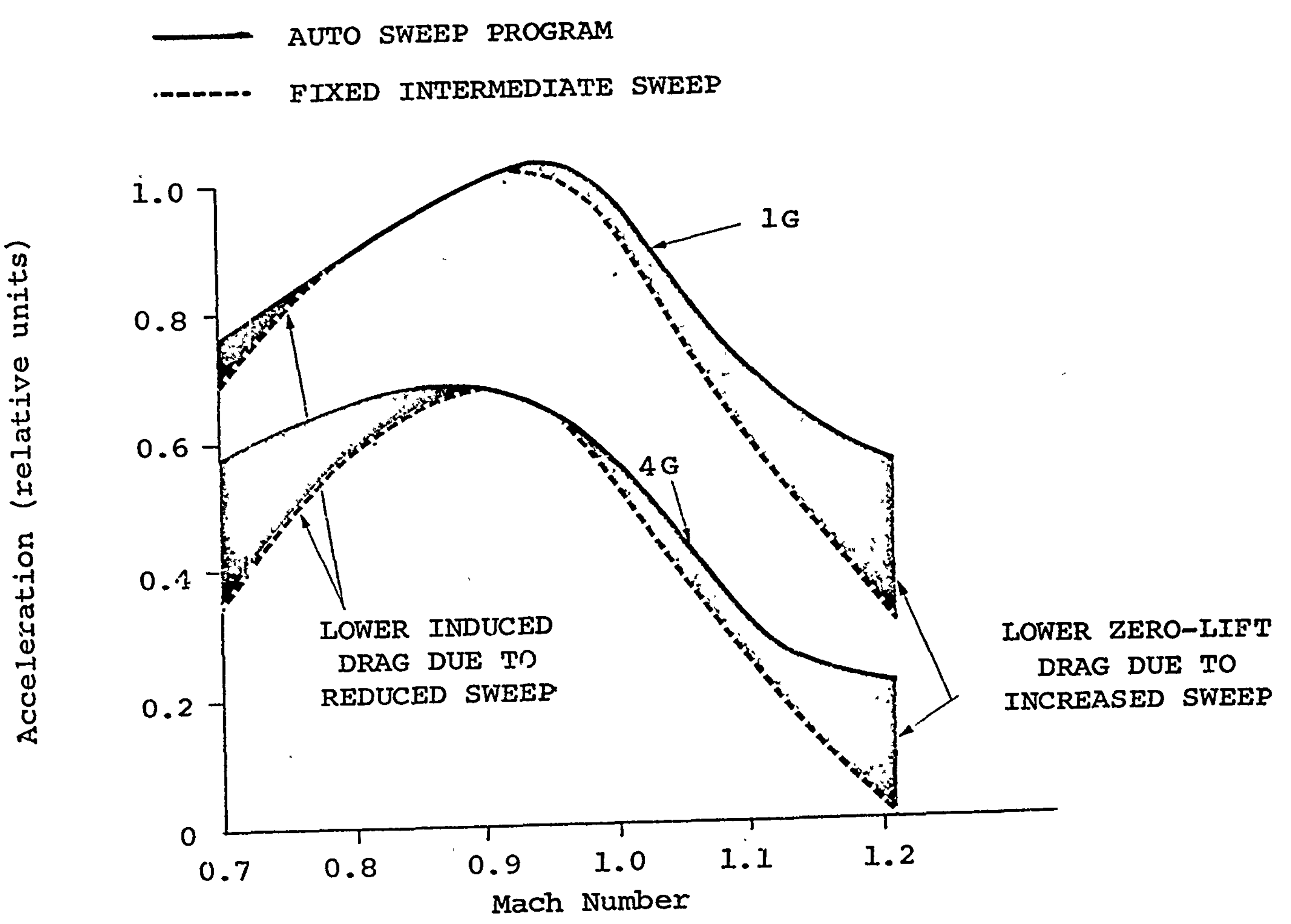


FIGURE 3.4. AUTO-SWEEP ADVANTAGES OVER FIXED SWEEP

(Source: Grumman Aircraft Corp.)

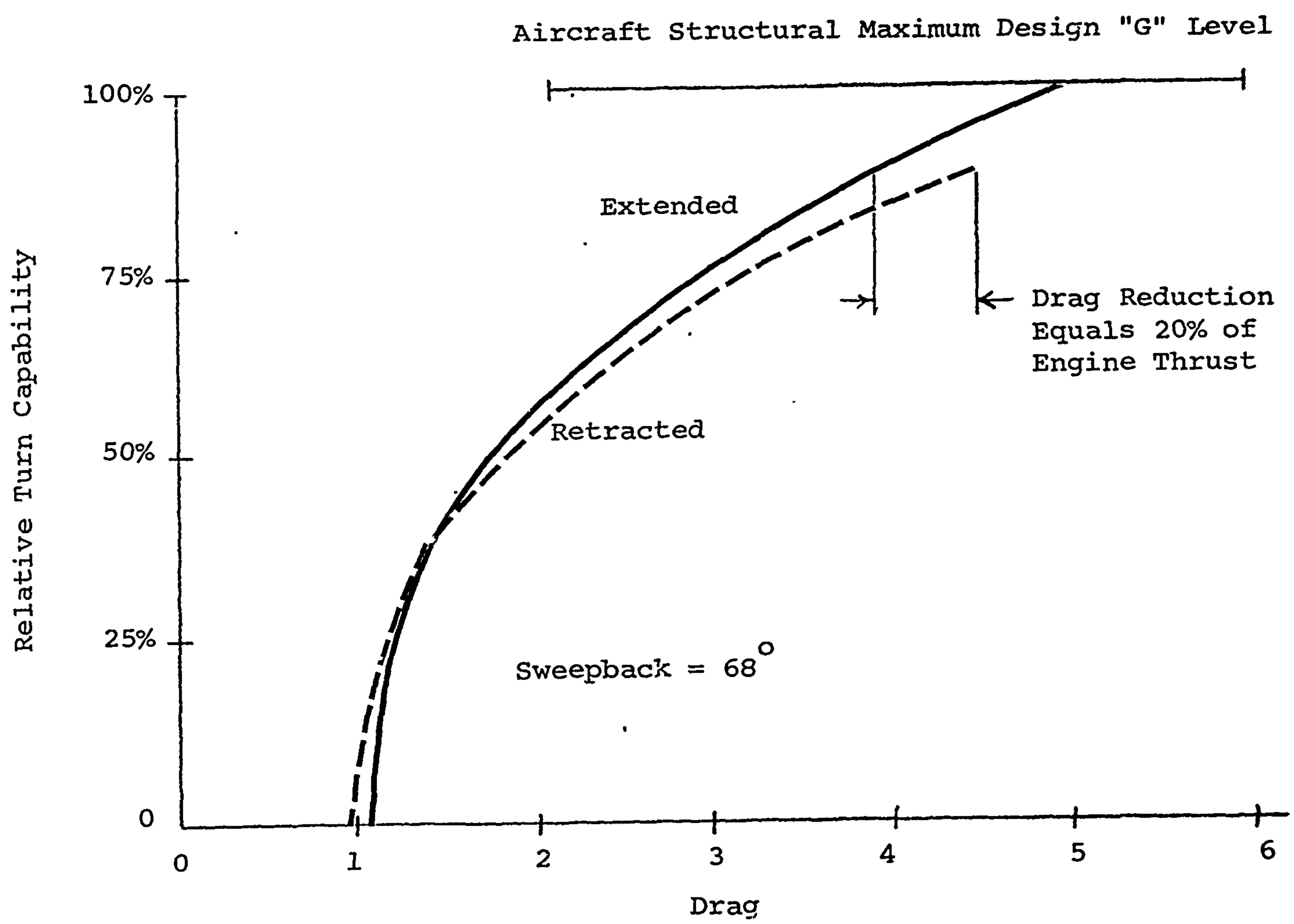


FIGURE 3.5. EFFECT OF SUPERSONIC GLOVE VANE EXTENSION ON F-14 MANEUVERABILITY

(Source: Grumman Aircraft Corp.)

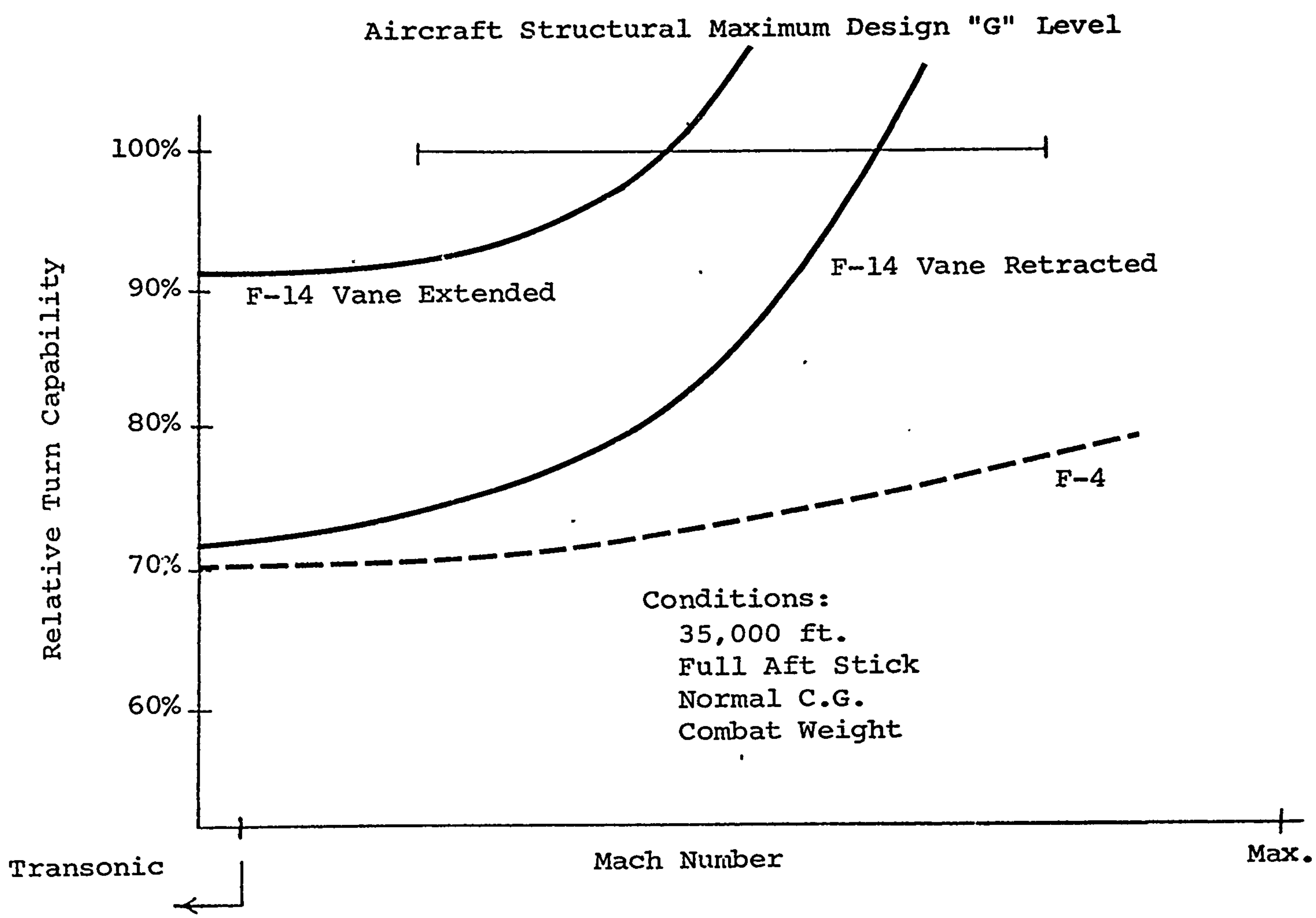


FIGURE 3.6. EFFECT OF GLOVE VANE ON SUPERSONIC MANEUVERING OF F-14 AIRCRAFT AS COMPARED TO F-4.

(Source: Grumman Aircraft Corp.)

ments such as new engines, new structural design, new weapons and fire control systems, new materials, etc. The F-14 has taken advantage of all available technical advances, within the constraints of price and time, to gain the best performance possible and permit multiple-mission capability.

It is the incorporation of these technological advances which is primarily responsible for the high unit cost of the F-14. What is most aerodynamically significant about the aircraft is Grumman's ability to exploit the advantages of the variable-sweep wing to the extent that the F-14 can outmaneuver all other known fighters operational in the world today. There is, unfortunately, no dollar figure on this achievement. However, it is a real and demonstrable capability -- one supported by the Navy test pilots, who are all unstinting in their praise of the F-14's flight characteristics.

In summary, the F-4 and the F-14 are both superior, air-superiority fighters designed originally for fleet air-defense. They are of comparable dimensions as dictated by carrier operations, but the F-14 is heavier and more expensive. The F-14, when coupled with the Phoenix missile system, makes the F-14 a superior fighter and a unique weapons platform. The F-14 offers improved performance over the F-4, but a far more sophisticated analysis is needed to assess whether the aerodynamic advantage alone is sufficient to warrant the additional cost. More precisely, the increased cost _must_ be justified by the improved effectiveness as a _weapon system_: the F-14 combined with the Phoenix missile and the AWG-9 avionics.

IV. DEVELOPMENT HISTORIES OF THE F-4 AND F-14

The Phantom II traces its history back to September 1953, when McDonnell Aircraft Corporation submitted an unsolicited proposal for the F3H-G, a single-place, long-range fighter/attack aircraft, designed as an improvement of the Phantom I. Mr. H. D. Barkey, Vice President, Aircraft Engineering Division, McDonnell Douglas Aircraft Co., St. Louis, Missouri, has emphasized that "The Phantom had its beginning not by winning an aircraft competition, but rather by losing one." Early in 1953, the Navy had conducted a competition for a carrier-based fighter plane which was won by the Chance-Vought F8U. Mr. McDonnell, Chairman of McDonnell Aircraft, and his assistant, David Lewis (now Chairman of General Dynamics Corp.) were determined that the McDonnell Co. was not going to be forced out of the carrier-based aircraft business. They therefore embarked upon a prolonged marketing campaign, in which McDonnell engineers canvassed many Navy personnel in the Bureau of Aeronautics, the Office of the Chief of Naval Operations, and indeed anyone who was willing to listen and provide information or fill in questionnaires regarding their preferences for the next carrier-based fighter aircraft. There were many studies and layouts made during the following year; indeed, a full-scale mockup was constructed of a design which was then believed to be most nearly representative of the desires of the majority of Navy operations personnel contacted. That model ultimately became the F-4.

A formal development proposal was submitted to the U.S. Navy by McDonnell in August 1954. The Phantom II was to be a single-place, but twin J65 powered, all-weather fighter armed with four 20mm cannons. The basic layout was similar to that of the Phantom I (the first jet-powered carrier fighter aircraft), the F2H Banshee series, and the Air Force F-101 Voodoo. The twin engines were expected to improve reliability and reduce attrition in both peace and war. Various structural and aerodynamic refinements were introduced, based on prior experience. Particular attention was focused on the horizontal tail, which was ultimately given a negative dihedral, mounted low on the fuselage in order to prevent the pitchup problems experienced with the F-101. Indeed, the tail design turned out to be one of the most difficult tasks in the development of the F-4. A major improvement was the installation of a variable-geometry engine air inlet which permitted good engine performance at all speeds and altitudes, and allowed the top speed to exceed Mach 2. The engine originally specified as the J-65 was replaced by the J-79 as soon as the latter was available, marking the usual history of fighter development in which improved performance engines are installed as early as possible. General Electric made better progress than anticipated with the J-79, and early in 1955 it replaced the J-65.

In October 1954, the Navy issued a Letter of Intent for the development of two prototypes and one static test aircraft, which were redesignated as the AH-1, reflecting the attack mission.

Following receipt of the Letter of Intent, Mr. McDonnell withdrew from direct participation in the project, which he turned over to David Lewis. Lewis worked with the Bureau of Aeronautics in an attempt to prepare a detailed specification for the AH-1. This was a very difficult assignment, as there was then no military requirement for the aircraft. After six months of futile attempts, the requirement was finally decided upon in the course of a 2-hour meeting at the McDonnell Aircraft plant in St. Louis, in April 1955. The mission was determined to be primarily fleet air defense: that is, the plane was to be deployed from a carrier, cruise out to a radius of some 250 nautical miles, stay on combat air patrol, attack an intruder when required, and then return to the carrier with a total deck cycle time of 3 hours. It was also determined that the airplane should be armed with air-to-air missiles of the latest type instead of guns. Specifications were firmed up and delivered to McDonnell in the form of a letter 9 months later.

Interestingly, the Navy admirals made their decision based on only three views and an inboard profile of the proposed airplane. There were no formal papers or other procedures such as are currently employed in the contract definition or concept formulation of a new aircraft weapon system. Indeed, the entire McDonnell proposal amounted to only an 8- to 10-page report.

The project proceeded on a basis of mutual trust between McDonnell and the Navy Department. There was not even a formal program manager until the initial flying date when David Lewis was named McDonnell program manager. Navy organization was handled by the "Class-Desk, Fighter" commander. There was no Pentagon program manager, such as is commonly employed today in the development of such aircraft.

The design of the F-4 was an iterative process throughout its history. That is, it was responsive to Navy requirements, and in turn, Navy requirements were responsive to technical capabilities. Design decisions were often informal, reflecting results of various meetings or even chance conversations, such as would now be prohibited under current DoD regulations.

For example, the story is told that the initial decision to employ two engines in the F-4 resulted from a conversation between a McDonnell engineer and the wife of a Navy pilot who remarked at one point during a friendly dinner that her husband was terrified of making carrier approaches in a single-engine aircraft.

The AH-1 designation was changed to F4H-1 on 26 May 1955, with the change of mission to a missile-armed fighter. A camera equipped reconnaisance version, to be known as the F4H-1P, was also planned. We have noted that during the course of these developments, the fighter had been reconfigured as a two-place aircraft, permitting all-weather fleet air defense. However, the attack capability of the original design was retained, which later led to the Phantom II being a logical choice for the U. S. Air Force Tactical Air Command.

The XF4H-1, a first version prototype, had its first flight on 27 May 1958. Designed for Mach 2 speeds, it actua ly achieved Mach 2.6 during its flight trials. The F4H-1 designation was subsequently changed to F4-A. The first true production model, the F-4B, appeared in 1961, three years after the first flight of the prototype, and six years after the initial specifications. These and the following events are noted on Table 4.1.

During the early development of the F-4 the Navy experienced a most serious technical setback elsewhere. Complete reliance had been placed upon the J-40 engine in other programs. Indeed, all the Navy's trans-sonic aircraft were originally planned

TABLE 4.1

DEVELOPMENT HISTORIES

Significant Events

F-4

1953

Sept. - F3H-G, Unsolicited Proposal

1954

Aug. - Formal Development Proposal
Oct. - AH-1 Prototype Letter of Intent

1955

May - Designation changed to F4H-1
July - F4H-1F (F-4A) Production Version Specifications
Aug. - F8J-1 Invitation to Chance-Vought

1958

May - F-4A First Flight (XF4H-1 Prototype)
Sept. - NPE I (Navy Preliminary Evaluation)

1959

Aug. - NPE II
Oct. - First Aircraft Lost

1960

Feb. - First Carrier Test
May - NPE III
July - No. 13 Aircraft Lost
July - BIS

1961

May - Aircraft No. 17 Lost
June - Aircraft No. 15 Lost
June - F-4B(G) First Production Models
June - First Fleet

F-14

1958

Eagle-Missileer Work Begun, Proposed Fleet Air Defense System

1961

Eagle-Missileer Cancelled

DEVELOPMENT HISTORIES (cont.)

F-4

1962

Aug. - Air Force Chooses F-4C for Tactical Air Command

Aug. - Deployment

1963

May - First F-4C Flight

1965

Mar. - First RF-4B Flight
Dec. - First F-4D Flight

1966

May - F-4J, Standard Navy & Marine Fighter First Demonstrated

June - F-4K for Royal Navy

1967

Feb. - First Flight F-4M (Improved F-4K)
Oct. - First Production F-4E Delivered to Air Force

1969

Nov. - Japan Ordered F-4E's
Nov. - Germany Ordered F-4E's
Dec. - Israel Ordered F-4E's

1970

RF-4E Reconnaisance Version

F-14

1962

F-111B Replaces Missileer. Eagle becomes Phoenix.

1964

$1.75 million Grumman Contract to Redesign F-111B.

1967

Nov. - VFX (GAC Unsolicited Proposal)

1968

Navy Fighter Study No. I - Feasibility Study
Apr. - Congress Cut F-111B Funds
June - F-111B Stop-Work Order
June - F-14 Contract Definition Study

1969

Feb. - F-14 R&D Contract Signed

1970

Feb. - "B" Engine Contract Awarded
Dec. - First F-14 Crashed on Second Flight

1971

Aug. - NPE #1 (Navy Preliminary Evaluation)
Oct. - Lot IV Option Exercised

1972

June - Second Crash
Aug. - NPE #3 Scheduled
Dec. - BIS Trial Scheduled

1973

Apr. - First IOC Fleet Operation Planned
48 F-14A's to be Delivered in CY '73.

around that single large turbojet engine, predicted at the time to have outstanding performance. But the J-40 did not live up to expectations and was finally cancelled. The Navy resorted to Air Force engines and initiated crash development programs to supply its own needs.

Alarmed by the collapse of its J-40 engine program, the Navy decided it would develop an alternative to the F4H-1 and the J-79 engine upon which it depended, to avoid the possibility of a similar situation developing. The Navy therefore, in August 1955, asked Chance-Vought to submit a proposal for an all-weather, missile only, single seat, single engine fighter, an improved version of the company's successful F8U-1, which was to be powered by the new J-75 engine built by Pratt and Whitney. Such a program, it was thought, would protect against the collapse of the J-79 and/or the F4H-1 program, or a discovery that there were basic concepts in either that were not sound. It was the Navy's intention to bring both aircraft into operational service with the fleet, if warranted. Fortune smiled, and both the new aircraft and engine proved highly successful. Now, however, the Congress would not grant production funds for both aircraft, The Navy chose the Phantom II primarily because of its two-man fleet defense advantage. The F-4's second engine was also considered an advantage from the reliability and effectiveness standpoints. Certain Navy civilian engineers who participated in the evaluation believe the cancelled F8U-3 eventually would have set even higher performance records than the Phantom II. Although the F8U-3 was not a prototype, its concurrent development with the F4H-1 was a close approximation to the currently proposed fly-before-buy prototype competition.

In the eyes of the McDonnell engineers and executives, the F8U-3 was a direct competitor of what was to become the F-4. They believed it was intended "to keep McDonnell honest." McDonnell's reaction to the introduction of the F8U-3 was to accelerate their own design efforts, primary among which were increased propulsion and introduction of a rear cockpit flight capability. The McDonnell executives think the F8U-3 possessed less air-to-ground capability, which they saw as a major reason for its failure in the subsequent competition with the F-4. In addition, the F-4 was designed with growth factor always in mind as a major influence on design. The McDonnell executives believe the F-4 always had much greater potential for growth than had the F8U-3. In any event, in 1958 the F4H-1, as the F-4 was then called, and the F8U-3 flew a side-by-side competition during a Navy Preliminary Evaluation (NPE) at Edwards Air Force Base. Navy pilots flew both aircraft and in direct competition decided in favor of the McDonnell product. The result was the award of a limited production contract for the F-4 Phantom II in December of 1958.

Phantom II contracted deliveries are listed on Table 4.2 through 30 June 1970. More than 4200 F-4's had actually been manufactured by the end of July 1972.

What lessons for today are to be learned from the history of the F-4?

Don Malvern, who succeeded David Lewis as McDonnell's F-4 program manager, attributes the success of the F-4 to a combination of good luck and good engineering.

In justice, one would also have to add, good marketing. It will be recalled that the early design changed continually as the result of interplay between newly developed Navy mission requirements and technical possibilities. Design is an iterative process in the aircraft industry by its very nature. However, whereas in the 1930's and 1940's one man could carry an entire design for an airplane in his head, today the wide variety of subsystems and the corresponding specialties required demand a team approach. Nevertheless, close interrelation between the customer and contractor is still required for any successful aircraft design.

R&D costs are not particularly sensitive to the multiple-purpose adaptability of an airplane, if such adaptability is designed in from the beginning, as it was with the F-4 (and, incidentally, the F-14 as well). The F-4 was designed as a fleet air defense, interceptor, dog-fight fighter and attack aircraft, ab initio. It has been DoD policy that such weapon systems should be multi-purpose to gain maximum cost-effectiveness. Whether or not adaptability or multi-purpose capability is in fact cost-effective requires a more detailed examination in each case. On the surface at least the argument is appealing. But as costs continue to climb, it may be that single purpose vehicles, such as remotely manned aircraft, may prove more cost-effective.

TABLE 4.2

F-4 CONTRACT SUMMARY

Contract Number & Date	F-4A	F-4B	F-4C	RF-4B	RF-4C	F-4D	F-4E	F-4J	F-4K	F-4M	#	Cum Total
NOas 55-272 (CPFF) 18 Oct 1954	7										7	7
NOas 57-186 (FPI) 19 Dec 1956	16										16	23
NOas 59-0245 (FFP) 25 Feb 1959	24										24	47
NOas 60-0134-i (FPP) 14 Aug 1959		72									72	119
NOw(A)61-0004-f (FPI) 31 Aug 1960		72									72	191
NOw(A)62-0383-i (FPI) 31 Aug 1961		147									147	338
NOw(A)63-0032-i (FPI) 31 Dec 1962		123	307		24						454	792
NOw(A)64-0001-f (FFP) 26 Feb 1964		125	275	9	89	52					550	1342
NOw(A)65-0100-i (FPI) 30 Sept 1964									4	2	6	1348
NOw(A)65-0044-f (FFP) 16 Apr 1965		124		27	128	222		18			519	1867
NOw(A)66-0606-i (FPI)* 30 Jun 1966									20	24	44	1911
N00019-67-C-0095(FPI)* 5 Aug 1966		4			96	519	99	152			870	2781
N00019-67-C-0673 (FPI)* 18 Aug 1967									28	92	120	2901
N00019-68-C-0495 (FPI)* 31 May 1968					64	(IR)16	245				325	3725
N00019-69-C-0521 (PRI) 30 Jun 1969		10			36 6(RF-4E)		207	68			327	4052
N00019-70-C-0099 (FFP) 30 Jun 1970								34				
N00019-70-C-0536(FFP) 30 Jun 1970					(GY)88(RF-4E)						154	4206
N00019-70-C-0559 (FFP) 30 Jun 1970							(IR)32					

* Successive Target

There are also lessons in engineering manpower to be learned from the F-4 program. The manpower growth of the F-4 was well-controlled. Initially, some 100 engineers were involved in October 1957; this number grew to 1,000 at the time of the F-4's first flight in May 1958. Of those, some 360 were design engineers. In 1967 there were a maximum of 3,100 engineers working on the F-4. Most of those were concerned with handling documents related to design changes for the various configurations of the aircraft, as demanded by the 28 different contracts then in effect. Even as late as July 1972, there were still 1,100 engineers so employed.

Incidentally, only 25% - 30% more engineers are presently required for the F-15 than for the F-4 at the corresponding period in its development.

Another interesting fact is that the initial design of the F-4 was that of about a dozen engineers. Organizational simplicity was a decided benefit in developing the F-4.

Part of the reason for the success in the development of the F-4 was the limited number of reports required. McDonnell Douglas believes that far more time and money would have been required if the F-4 had been developed under today's DoD procedures and report requirements. Particular support for this view was given by the events leading to the decision to produce the F-4E. In the view of McDonnell Douglas that decision was unduly prolonged by DDR&E and DoD systems analysts. Numerous reviews were required which consumed far more time in preparation and defense than had previously been required to initiate development and production of earlier F-4 models. In the words of Mr. Barkey, "The (F-4) program was a success primarily because of the mutual understanding which existed between the contractor's project engineer and program manager. Fortunately, the Phantom was developed before the day of the heavy emphasis on the 'ilities' and the complex decision-making processes."

It might also be noted that, although the F-4 was subject to continued Congressional review, it was not subject to the kind of harassment experienced by the F-14. The need to defend an aircraft program repeatedly and to prepare annual data for appropriations must delay development and increase costs when as much effort is required for the preparation of the necessary documents as has been the case with all aircraft, particularly the F-14. Congress should consider joint hearings by House and Senate committees and the possibility of multi-year funding with Congressional review at limited, predetermined intervals during the development cycle of weapon systems such as the F-4 and the F-14.

Returning to the DoD management procedures, the McNamara regime's cost awareness was a very definite positive factor, but the McNamara requirement for detailed management control from the top is often viewed as a decidedly negative factor. Proper aircraft development requires decentralized management in the opinion of many aircraft engineers.

A closely related problem which has grown steadily since the F-4 was first proposed is that of management layering and excessive staffing. This is a problem which has been studied and documented over the past 15 years with no apparent improvement. It is generally agreed that such layering exists in both Government and industry organizations, and that a significant if undefinable cost is associated. Decentralization could help minimize both problems.

Another DoD attitude which does not appeal to industry engineers is the undue importance given by Defense Department systems analysts to small differences in cost-effectiveness. Policy decisions should not be made on the basis of a 1% or 2% difference in some cost-effectiveness index. In such calculations, those indices are subject to rather extensive simplifications and assumptions. To be truly effective, cost-effectiveness indices should display wide variances.

The early F-4 models evolved without the benefit of management procedures later developed under Secretary McNamara. As we have noted, the situation deteriorated with the introduction of systems analysis review of the F-4E. DoD lost a considerable advantage when it turned to the arm's-length approach required under present concept formulation and contract definition procedures. Concept formulation and contract definition evolved under the McNamara regime in order to counteract "cronyism". They give a degree of standoffishness in contract award which is desirable, but lead to dialogues which are often less than candid and which prohibit the iterative design approach which was so successful with the F-4, in the view of McDonnell engineers.

Overall, the experience with the F-4 substantiates the recommendation of the Commission on Government Procurement that "management layering, staff reviews, coordinating points, unnecessary procedures, reports, and paperwork on both the agency and industry side of major weapon system acquisitions" should be minimized.

Turning to the F-14, although the F-14 R&D contract was signed in February 1969, the history of the F-14 stretches all the way back to 1958, when work was initiated on a proposed fleet air defense system known as the Eagle-Missileer. The Missileer was to have been a long endurance, subsonic (relatively slow speed) missile carrier with a very prolonged loiter capability. It was to have been equipped with a high power pulse-doppler radar that had track-while-scan multi-shot capabilities. (It would have been capable of firing multiple missiles against multiple targets.) The missiles themselves were to have been a new long-range (100-mile) air-to-air type called the Eagle, of which the Missileer was to have carried six.

The primary target for the Eagle-Missileer was the Russian long-range bomber which was thought to offer a significant threat, particularly with nuclear weapons, against aircraft carriers. The Eagle-Missileer program was cancelled in 1961. The Missileer aircraft was considered to be too slow and was contrary to the philosophy of DoD, which then as now supported multiple mission aircraft.

It was decided that the Eagle-Missileer would be replaced by the F-111B --the Navy version of the fighter/bomber which grew out of the ill-starred TFX program --with the Eagle missile transformed into the appropriately named Phoenix. It became apparent over the succeeding years, during which the F-111 encountered one problem after another, that the F-111B could not be satisfactorily adapted to carry the Phoenix missile and still maintain its weight low enough for carrier operations.

Newspaper columnist Jack Anderson* charges that the Naval Air Systems Command Program Manager awarded a secret $1,750,000 contract to Grumman in 1964 to redesign the F-111B. Anderson

*Washington Post, April 30, 1972

asserts that that contract permitted Grumman to assemble the team which later enabled them to put together the winning VFX proposal. At that time, Grumman Aircraft Corporation was subcontractor to Convair for the F-111B version of the TFX. Grumman therefrom acquired valuable experience in the design of the swing-wing aircraft, in the use of titanium, and familiarity with the new bypass turbofan engines. It was this experience, rather than the study, which gave Grumman a favored position in subsequent bidding on the F-14.

Recognizing the problems the F-111B presented, Grumman Aircraft presented an unsolicited proposal to the Navy in November 1967 for what became known as the VFX. The Chief of Naval Operations subsequently initiated an internal feasibility study of the proposed VFX. That study, the first Navy Fighter Study (NFS), concluded that the new fighter was feasible and the Navy was authorized in June 1968 to proceed with Contract Definition. Five companies submitted proposals. The two finalists were Grumman Aircraft Corporation and McDonnell. Those two were asked to resubmit cost bids, together with certain changes. Just prior to contract award, Grumman revised their bid downward by $474 million, while McDonnell Douglas raised theirs $100 million. Even so, Grumman Aircraft Corporation's bid was still higher than that of McDonnell Douglas. (It was in fact the middle estimate of the five original bids.) Nevertheless, the Navy awarded the contract to Grumman in February 1969 on the basis of technical superiority. There is no reason to doubt the technical decision; but the circumstances surrounding the last minute $474 million reduction suggest it probably should be considered a buy-in.

Certain Naval Air Systems Command individuals who are familiar with the history of the negotiation for the Grumman F-14 contract believe that the contract was far more favorable to the Navy than the Navy originally had anticipated. In the bargaining sessions, the Navy initially adopted certain rather extreme positions which, to their surprise, were accepted without protest by Grumman. Indeed, Grumman offered conditions far more advantageous to the Government than the Navy negotiators had expected. The whole contract itself was very harsh. Essentially, it is a fixed-price contract with incentives. The contract ceilings for the various lots are too low and inflexible. Under the so-called Varlot formula, the unit cost for minimum production quantities is about 5% greater than the target cost. Comparable increases of some 15% and 24% are permitted under the S-3A and F-15 contracts. And on their own initiative, Grumman reduced their ceiling from 130% to 125% over target cost, a figure to our knowledge lower than had ever been negotiated before. Yet, the Navy accepted the lower figure as being in the Government's interest, even though, as is now apparent, it did not leave sufficient room for possible subsequent growth.

A similar position developed in the contract's inflation escalation clause. Grumman agreed to accept a 2% material and 3% labor average annual inflation-induced cost growth at a time when inflation was rampant and was nearer 6%. Once again, the Navy accepted the lower figure as being to the Government's benefit. A more extreme escalation clause would have been more fair and fitting, as has again been borne out by events.

In contrast, the McDonnell F-15 contract has a contract ceiling of 150% and is in essence cost-plus-fixed-fee, which leaves ample room for escalation, whatever the cause.

The lessons to be learned are: that negotiations for such contracts should not be conducted on a strict adversary basis, as has been the practice in the past; and that technical evaluators should be given access to cost data. Such access would help discover potential buy-in situations. An attempted buy-in would be readily apparent to a combined Navy team and would not be accepted, even though it might apparently be to the financial advantage of the Government to do so in the short term. The Navy negotiators, financial and technical together, should search for clauses and restrictions which would certainly benefit the Government, but which would not be excessively harsh on the contractor or impractical in the evaluators' best judgement. Future negotiations should be undertaken by the Navy in this fashion so as to guarantee a fair rate of return to the contractor as well as monetary benefit to the Government.

In December 1970 the first F-14 airplane -- a fixed wing version -- crashed on its second flight due to a hydraulic failure. (The only other significant technical problem previously reported in the open literature was the failure of the wing box of an F-14 under static test in June 1970.) The crash resulted in an 8-month schedule slippage and forced the F-14 development program into a situation -- similar to that of the F-111B -- in which production models will be turned out before the test and evaluation series has actually been completed. As a result of the crash, the first Navy Preliminary Evaluation (NPE) was postponed 8 months, until June 1972, when a second crash occurred. The Navy also deferred the start of its Board of Inspection and Survey (BIS) trials until February 1973, a slip of 8 months.

Because of the postponement of the BIS trials, an additional contract option, Lot V, originally due to be exercised October 1, 1972 for an estimated 48 production aircraft, will be due before the BIS trials commence. In September 1972 Congress postponed this decision date to December 31, 1972. Grumman has said they will not undertake the production of further aircraft, including Lot V and the succeeding lots, without renegotiating the contract. This is a current problem not as yet resolved. If, however, Grumman accepts the responsibility to produce Lot V, the result would be that a total of 134 aircraft would be on order before the final results of the Navy BIS trials on performance, maintainability, and reliability become known.

The hydraulic failure which caused the first F-14 crash, was a freak accident and was quickly remedied. (Incidentally, the problem originated in the use of titanium in the hydraulic system.) However, the development of the "B" engine, the F-401, has led to more radical problems.

In the original planning for the F-14 and F-15, DoD required that a common engine be used. This, the so-called "B" engine, was to be developed new, because existing engines would not meet the anticipated needs. The TF-30 or "A" engine was proposed only as an interim power plant to obtain flying experience on the first 66 F-14's until the "B" engine was available for installation on the 67th. (The F-15 was planned initially to use only the new engine.) Because of problems with the "B" engine (detailed later), during FY-71 this plan was changed so that the first 301 F-14's would employ the "A" engine. The development of the F-14B was deferred until the "B" engine development problems were solved.

Initially, 1,928 "B" engines were called for. Of those nearly 2,000 engines, the first five were to be experimental, the next 33 were considered as prototypes, and the remainder were production units. The Navy cancelled its planned FY-72 buy of these new engines on July 1, 1971, and deferred purchase of the F-14B's in which they would have been mounted. The "B" engine has been the principal technical problem in the development of the F-14.

The history of this engine problem is informative. In August 1968 a projected Initial Engine Development of 18 months was begun by DoD as a joint Navy/Air Force program. P&W and GE bid on developing, building, and testing a prototype. In June 1969, both contractors submitted proposals to Navy/AF for the engine. The F-14 version of the engine, to obtain desired performance, was planned to pass about 20% more air through its fans than the F-15 version. However, it was thought possible to retain a common core (compressor, diffuser, combustor, and turbine) with different fans for the two versions. On March 1, 1970 P&W was given a $410,034,000 contract to develop, qualify, and deliver an X-engine for flight test: the F41-PW-400 dual-spool engine. This engine was to be smaller, lighter, and have more thrust than the TF-30.

The new engine was to achieve the projected improvements by:

a. running the turbine inlet 300°F hotter than previous engines.

b. using light-weight, high-strength discs formed by powder metallurgy (a new concept, developed by P&W under Navy sponsorship).

c. using a newly developed (PW/Navy) process to form blades with alloy grain parallel to length.

d. using metal honeycomb structures for lightness.

e. using more than customary amounts of titanium for lightness in fan construction.

The end result was to be an engine thrust/weight ratio of 8½:1 versus earlier values of 5:1.

Difficulties began to appear early in the program, and the production schedule lagged while engine performance problems were being solved. The following problems of particular difficulty were resolved in the manners indicated:

a. Flutter in first and second stage compressor blades (airfoils were redesigned).

b. Third stage compressor blade stall margin too low at 102% flow (blades were made wider).

c. Compressor efficiency about 2% low in high altitude cruise (selection of airfoil, a balance between efficiency and stall, had to be reconsidered).

d. Combustor performance was good, but durability was poor. One engine was lost from this cause. (Redesign of components) Efficiency was 1.25% low at altitude.

e. High pressure turbine efficiency 2.6% low at altitude and high speed.

f. Low pressure turbine (fan drive) efficiency 2% low.

g. Fuel consumption curve dropped badly.

The deficiencies, each small in itself, added up to a 20% thrust deficiency at M2.2 speed and high altitude (although sea level performance was acceptable) and an overrun of $122 million.

The contractor had set his goals high (to get the contract?) and engineering review by Navy/AF teams from service laboratories, NavAir, and Wright Field had approved them.

In March 1971, P&W requested additional funds on its CPFF contract to remedy the defects. The situation was worsened by the fact that P&W had permitted (in the interest of getting the contract?) the USAF to negotiate their original price downward. Now, in addition to the engine problems, P&W claimed added expense, to be laid to the engine, by reason of their own business-base decline.

The program was re-evaluated in April 1971. On an overrun of $122 million caused by the preceding R&D problems, the AF and Navy each took $55 million and P&W absorbed $12 million. A new fan and compressor were designed for what was to be known as the Series II engine. The USAF would accept a limited number of Series I engines in order to get the F-15 into the air on schedule. Three Series I engines delivered to Grumman in June 1972 were bailed back to P&W. In December 1973 it is expected that an engine which will perform to within 5% of specification throughout the flight envelope is to be delivered to Grumman. This schedule represents an 8-month slip for the F-14B. (Note: production engines must be 2% to 4% <u>above</u> specification minimums on other engine models.)

The USAF will use Series II engines on production F-15 aircraft, but the presence of Series I engines in early aircraft requires that the USAF support the development of two engines instead of one, which will affect the cost of the F-15 program. The Navy now looks to the Air Force for the successful development of the "B" engine.

Testing of engines and components is being done by the Government at Trenton (Navy) and Wright Field (Air Force) to save expense. The imposition of the requirement for mutuality had led to the design being burdened with two sets of specifications, requirements for engineering data, and associated management reports. This area has been gone over by Navy/AF three or four times, in an effort to reduce the burden. Nevertheless, review of the Engineering Change Proposals (some 60 by mid-72) indicates a preponderance of proposals to still further reduce tests and data requirements (and not all such proposals were accepted!). To date, about $10 million worth of tests and data submittals have been cancelled.

Agencies exist in the Navy and USAF for reducing the number of MIL Specs, and for making existing specs common to all services. The problem is they cannot reconcile different MIL Specs for the same aircraft intended for different missions by the different services. Mutual designs like the F-111 and F41-PW-400 have suffered, and future attempts at mutuality will continue to suffer commensurately, until specification standardization is agreed upon.

Because the F-14 is in some sense a successor to the F-111B, it is believed -- and indeed it has for the most part proved to be -- that its development is less risky than was the case with the F-111. The reason for this belief is that the F-14 uses much of the technology developed for the F-111B. It employs the same "A" engine as was intended for the F-111B, the Pratt and Whitney TF30P-412 turbofan engine with after burners. The F-14 swing-wing -- though much improved -- is based upon that of the Grumman swing-wing F10F and that of the F-111B. The use of titanium in the airframe for the F-14 also benefited from Grumman's prior experience with the A-6 and with the F-111B. Finally, the F-14's prime weapon, the Phoenix, was taken over directly from the F-111B program. The Hughes Aircraft AWG-9 fire-control avionics development was begun as part of the F-111B program, as was the long-range Phoenix missile itself, the AIM-54.

This, then, has been the history of the F-14 aircraft development to date. As will have been seen -- although it has encountered technical problems with the hydraulic system, which resulted in the crash of the first plane, and particularly in the development of the "B" engine -- for the most part, the F-14 development has been straighforward and without serious mishap until the second crash in June 1972, which was due to pilot error. The philosophy of basing much of the F-14 technology on that originally developed for the F-111B has proved itself. However, the problem of concurrency between early production and acceptance tests has not yet been confronted, and may lead to other difficulties requiring retrofit for correction. Nevertheless, technically the plane is sound, and its aerodynamic performance meets all specifications. The remaining problems, to which the F-14 critics address themselves, are those of unit cost and cost growth, which are discussed in the following chapter.

V. COST ANALYSIS

The F-4 unit cost history is diagrammed in Figure 5.1 for U.S. Navy versions using data derived from DoD budget submissions with then-current dollar values. (The number of aircraft delivered in each fiscal year is also indicated beside the corresponding unit cost point.) The overall F-4 production learning curve is only suggested by the F-4A/B points on Figure 5.1. It is not the true learning curve because it only shows the U.S. Navy aircraft cost history, and does not indicate deliveries to foreign purchasers. The unit-cost figures shown are fly-away costs for each fiscal year; they are not program unit-costs. Nevertheless, it is interesting to note that the unit cost for each of the first two F-4's delivered in FY '55 amounted to $75.8 million. This figure is misleading for the reason stated, but it does show the original cost of the F-4 was quite high early on its learning curve. This fact should be expected, as it is typical of the early production costs of fighter aircraft, but it is often forgotten in analyzing the early costs of the F-14, for example.

All of the F-4 costs shown are what would now be termed production dollars. No R&D funds were identified as such during the early development of the F-4, simply because it was not then the practice of DoD to separate the two funding uses. It is particularly difficult to estimate the R&D portion of any aircraft development program. Thus, whereas the production phase of the F-4 ran almost exactly on the estimated schedule and targeted cost, according to Mr. A. L. Boyd, McDonnell Douglas Treasurer, the R&D phase experienced an approximately 25% overrun.

Aviation industry overhead rates have changed radically since the F-4 was initiated. According to a recently completed internal McDonnell study, the combination of overhead and inflation would have caused R&D costs today to be greater by a factor of 2.57 than they were in 1955 when the F-4 was begun. The combination of direct labor and overhead costs have increased at an average annual rate of 7% according to that study. As a result, today the overhead rate at McDonnell Douglas is approximately twice that of 1954.

In spite of that cost growth, the F-15 avionics today are less expensive than the early F-4 electronics would be in today's

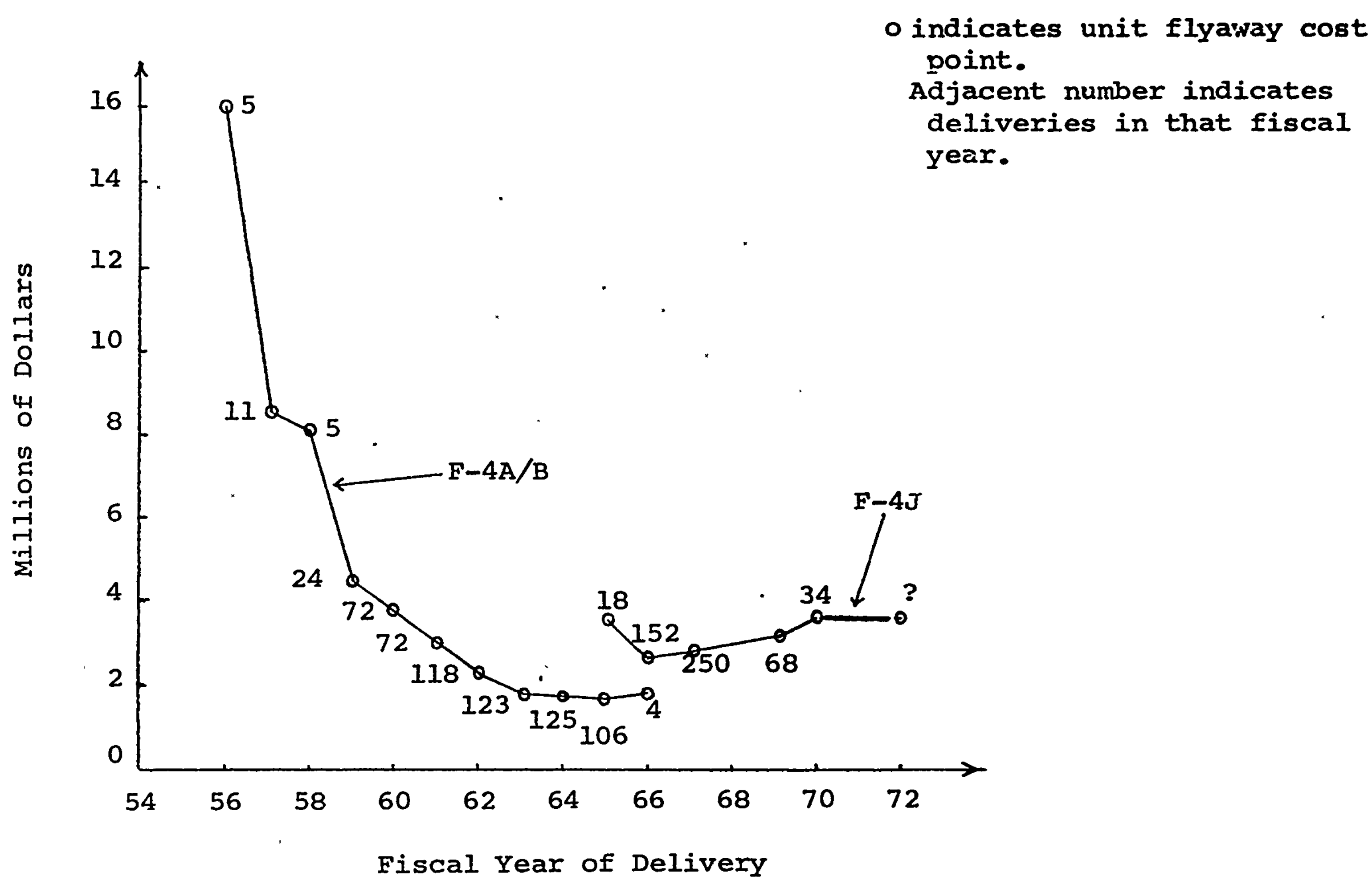


FIGURE 5.1: F-4 UNIT COST

(Source: George A. Spangenberg
Naval Air Systems Command)

dollars. Furthermore, the more modern electronics have far better reliability with correspondingly improved mean time between failures and reduced life cycle costs. (Incidentally, McDonnell estimates it would be possible to modify the F-15 for carrier operations at a unit cost increase of only 10%, if it were <u>not</u> required to carry the Phoenix missile.)

The sudden jump in cost between the F-4B and the F-4J depicted in Figure 5.1 in FY '65 was caused by the introduction of the AWG-10 avionics and associated design changes. The F-4J history is most interesting, as it reflects the rapid economic inflation experienced by the aerospace industry in the late 1960's. The FY '72 F-4 unit cost, indicated by the question mark on Figure 5.1, is estimated to be about $3.5 million, or about the same as the original F-4J unit cost in FY '65.

For comparison, the cost of the Air Force version of the F-4, the F-4C, was somewhat lower than the F-4B. The F-4C equipped with the standard Air Force avionics package and four Raytheon Sparrow III missiles cost between $1.7 and $1.8 million in 1966.

When contrasting the unit cost of an F-4 with an F-14, which at first appears so disadvantageous to the F-14, it is enlightening to compare the cost of the F-4 with that of the earlier North American Aviation F-86, the most popular jet fighter prior to the F-4. Some 6,200 F-86's were produced. The cost of an F-86 averaged somewhat less than $1 million. Since the advantage offered by the F-4 over the F-86 is something like that anticipated for the F-14 over the F-4, a unit cost differential of 2 to 4 (depending on which fiscal years one employs) would seem reasonable between the F-4 and the F-14, such as was accepted between the F-86 and the F-4.

If costs are controlled, the growth in cost of fighter aircraft from one generation to the next is explained -- after inflation is removed -- primarily by the increased capability represented by the new generation, especially in avionics and improved aerodynamic performance. According to an in-house McDonnell study the ratio of the cost per lb of one military aircraft over the cost per lb of a commercial airplane of the same era has remained constant. Thus, the cost ratio of the F-4 to the DC8 on a per lb basis is the same as that between the F-15 and the DC10.

Assuming that this study of McDonnel is correct and taking as a fact that the cost ratio between successive generations of military and commercial aircraft has remained the same, it follows that the actual growth of military airplanes may be determined by the same factors as the cost growth of the commercial transport airplanes. Therefore, technical factors, rather than poor cost control, are primarily responsible for cost growth of successive generations of fighter aircraft.

For yet further comparison, a total of 742 B-52's were manufactured by the Boeing Corporation at an average cost of approximately $8 million per plane. The current B-1 bomber has a projected unit cost of $45.4 million. The ratio of contemporary fighter to bomber costs probably has thus also remained the same over the past decade and a half.

A factor working to the disadvantage of the F-14 in any cost comparison with the F-4 -- indeed, to the disadvantage of all contemporary fighters as well -- arises from a particular technical consideration: heating caused by aerodynamic friction at supersonic speeds. Although the F-14 is faster, the speeds of the F-4 and the F-14 are roughly comparable because of this heat barrier. The technology is such that to build a Mach 3 or Mach 4 fighter with adequate range and load carrying ability would require an aircraft of approximately 100,000 lbs., or twice that of the F-14. The extra weight arises from the need for totally new heat resistant structures and subsystems. In addition, the new aircraft configuration would be poor for short landings and takeoffs, and during low and slow weapons delivery. Thus, we seem temporarily to have struck a speed plateau in the construction of military fighter aircraft. This fact accounts in part for the increased costs of modern aircraft associated with diminishing performance gains over prior generations. That is to say, current aircraft are at a point of diminishing returns where more money is required for marginal performance improvements.

Turning to the cost analysis of the F-14, there is a virtual plethora of unclassified information available. The key sources are Congressional hearings, conducted primarily by the Tactical Air Power Subcommittee of the Senate Armed Services Committee in conjunction with the latter's annual appropriations hearings, and reports prepared by the General Accounting Office (see bibliography).

As reported in the previous section, the Navy and Grumman Corporation signed the F-14 research and development contract in February 1969. That contract provided for eight production options for deliveries totaling 469 aircraft. Each option, which was known as a Lot and given a corresponding Roman numeral, was to be exercised by the Navy in subsequent fiscal years, subject to certain agreed limitations in maximum and minimum numbers. Decisions as to these Lots for each fiscal year have to be reached prior to October in each year. The Navy exercised Options I through III, totalling 30 aircraft through FY '71. Extensive hearings by the Senate Tactical Air Power Subcommittee were held on the F-14 in April 1971 and again in 1972, partially in order to determine whether or not the Navy should exercise its Option IV for 48 aircraft in FY '72 and Option V in 1972. The 1971 option was exercised, but the same issue developed with even greater urgency at the 1972 hearings. At that time the Grumman Corporation stated they would not accept any further Navy contracts for Lot V and subsequent options, unless the basic contract were renegotiated to permit a higher unit price.

The forty-eight 1971 Option IV aircraft were the minimum number which the Navy could elect to procure without breaking the contract. Similarly, in 1972 Congress ordered the Navy to make the minimum purchase possible under Lot V, which was to have been exercised prior to October 1, but that decision was postponed by mutual agreement until December 1972.

There are two primary controversial aspects concerning F-14 costs: the initially high unit cost estimate; and the subsequent cost growth during actual development.

Why was the original estimated unit cost of the F-14 so much greater than that of the F-4? The answer rests upon two primary factors: the effect of inflation, which has seen the Consumer Price Index grow at an average 3% annual rate; and the effect of increasingly sophisticated and complex technology. Both of these factors are analyzed in the following chapter.

The Comptroller General of the U.S., in his cover letter to a report reviewing the F-14 aircraft costs prepared by the GAO for the Joint Economic Committee of the Congress of the United States, emphasizes that, "In the beginning of any new weapon system development, there tends to be a certain amount of bias on the part of both the military service that wants to deploy the new system and the contractors that want to manufacture and sell that system. This bias may result in unrealistically low estimates of the cost to acquire the system, optimistic estimates of the time it will take to develop and produce the system, and optimistic estimates of the performance that will be provided to the operating forces." The Comptroller General noted that there were two fundamental factors which accounted for this situation: the competition for limited Department of Defense funds among the various service advocates of military weapons systems; and the fact that when contractors compete, they are "placed in a position of having to propose a cost that is within the already optimistically low funding level. (For) to do otherwise could mean the loss of a multibillion dollar contract."

As the Comptroller General makes clear, there is great pressure upon both DoD and its weapon systems contractors to submit low initial estimates. Congress must accept its share of responsibility for creating that climate. As we shall demonstrate in the following chapter, the actual historical costs of fighter airplanes follow a predictable rising regression line. The so-called cost growths, which so annoy Congress, result primarily from low initial estimates generated by everyone's optimistic desire to keep costs down.

The Congressional pressure on DoD to keep costs low creates a climate inducing very optimistic cost estimates by both DoD and its contractors. Congress should establish its own cost analysis staff to help determine reasonable estimates based on its own parametric analyses.

The General Accounting Office has found that historically all weapon systems have shown an average cost growth of some 30% over initial estimates. We have seen the F-4 experienced a 25% overrun in its R&D phase, and we shall see the corresponding F-14 figure was 28%. To enforce more realistic future estimates, Congress should take two steps:

1. It should anticipate higher costs for succeeding generations of increasingly complex weapon systems, using parametric projections to foresee the probable future costs; and

2. It should impose appropriate sanctions -- such as disqualification from future bids, loss of profit, dismissal, or demotions -- upon contractor and defense department executives who are responsible for proposing and accepting initial low estimates on winning bids which subsequently result in unacceptably large overruns as defined by parametric analysis.

The Comptroller General's emphasis on the pressure upon a corporation for low initial estimates reflects one of the more interesting aspects of the cost history of the F-14. In the previous chapter we noted that just prior to the contract award in February 1969, Grumman submitted a reduction in its bid totaling $474 million. It is an intriguing figure. Grumman's projected loss on the F-14 program was estimated in 1971 at $367.4 million on an aircraft buy of 313 F-14's (a number which had been reduced from the initial 469 aircraft on which Grumman had made its original bid). Grumman estimates a loss of $556 million would have been incurred if it had produced the 469 aircraft under current contract terms. It thus would appear the GAC's original bid, before the $474 million reduction, was a far better estimate of the actual development cost. GAC's last-minute reduction not only won the award, but very nearly equals the actual loss thereafter incurred; it is the primary factor responsible for Grumman's current financial difficulties.

The final and successful GAC bid of $2,419,650,000 was still higher than runner-up McDonnell Douglas' $2,319,422,000. Before the $474 million reduction, the GAC initial bid had been $2.894 billion. The original Navy estimate had been $2.893 billion. The remarkable similarity of these two independent estimates has never been explained, but it speaks well for the accuracy of parametric forecasting.

A Navy review team in March 1971 investigated what factors had been taken into account in this $474 million reduction. They were advised by Grumman that there were three, as outlined in the following Table 5.1:

TABLE 5.1: BID REDUCTION FACTORS

1.	Elimination of General and Administrative Expenses Applied to Government-furnished Equipment	Savings - $112 million
2.	Reduction of Procurement Cost Estimate	Savings - $197 million
3.	Reduction of Ceiling Margins on Grumman's Cost	Savings - $165 million

Certain facts relating to these three factors were brought out in the Congressional hearings by the Tactical Air Power Subcommittee. First, it was noted that the ceiling margin had been reduced to 125%, one of the lowest margins in history on such a procurement. Second, the reduction of the procurement cost estimate was a decision by Grumman reflected in an arbitrarily imposed 7% reduction in subcontractor contracts, which was not actually negotiated with the subcontractors at the time the reduction was made. Third, the elimination of General Administrative expenses on Government furnished equipment was a bookkeeping change in line with Navy directives, but in fact reflected accounting elements which had to be supported by some contract and which would be aggravated by a reduction in business base such as Grumman actually experienced subsequently.

To understand the implications of these factors, it is necessary to have a picture of the cost history of the F-14 program as it actually developed. This overview is presented in the following Table 5.2:

TABLE 5.2: F-14 COST HISTORY

Date	Quantity	Estimate ($)	Program Unit Cost ($)
13 Jan 1969	469	6.166 billion	13.1 million
30 Jun 1969	469	6.373 billion	13.6 million
30 Jun 1970	722 (proposed)	8.279 billion	11.5 million
23 Apr 1971	722 (proposed)	9.372 billion	13.0 million
30 Jun 1971	313	5.212 billion	16.6 million
31 Dec 1971	313	5.267 billion	16.8 million

The 722 quantity represents the Navy's stated requirement covering 25 F-14's for each of 15 aircraft carriers, plus 250 F-14's for the Marines, and approximately 100 for training purposes. The cost growth in the total program estimate -- rising from an initial $6.2 billion to a proposed $9.4 billion from January 13, 1969 to April 23, 1971 -- led the Armed Services Committee to recommend reduction in the quantity purchased to 313, with an estimated total program cost of $5.2 billion. The program unit cost of the F-14 thus grew 28%; almost the same as the 30% average cost growth found by the GAO to pertain to all modern weapon systems in its March 1971 study.

Congressional testimony brought out that there were six interrelated causes of the F-14 cost growth subsequent to contract award:

1. Increased overhead charges due to a drastically reduced Grumman Aircraft business base;

2. Increased inflation, more than twice as high as anticipated in the initial estimate;

3. Decreased numbers of production aircraft over which to spread the increased R&D costs;

4. Higher development costs than anticipated, particularly of the F4-1 or "B" engine;

5. The December 30, 1970 crash of the first test aircraft;

6. Contractor initiated design changes needed to meet Navy specifications.

(Item 4 may also be read: "poor original estimates")

In the case of inflation, it was noted in the preceding chapter that the Grumman February 1969 contract assumed an annual labor rate of inflation of 3%, and a material rate of 2%, when the Consumer Price Index inflation rate in 1969 was 6%. Inflation is studied more carefully in the next section. However, it is enlightening to observe that, in contrast to GAC's 3% labor inflation estimate, Hughes Aircraft -- prime contractor for the Phoenix AIM-54 and AWG-9 avionics systems -- planned on a 5% inflation in their bid. These programs have both remained on target technically and financially.

The crash of the first test aircraft and the subsequent 8-month delay in the test program resulted in what is estimated to be a $40 million increase in R&D funds. Of this amount, $8.7 million covers costs of investigations, and the remaining $31.3 is for so-called "stretch costs." The exact figure is in dispute, with the Navy and Grumman differing slightly as to the actual "stretch cost" total.

The history of the F-401 or "B" engine has been adequately covered in the prior chapter. It need not be repeated here, except to repeat that the total R&D overrun was $122 million.

Contractor initiated design changes were investigated in detail during the 1972 F-14 Congressional hearings. To that date, GAC had initiated and paid for $280 million in such design changes. The subcontractor's costs were themselves also higher than estimated for three other reasons: the effect of inflation and reduced subcontractor business base; initial underestimation of subcontractor costs by Grumman (see discussion on $474 million reduction); and changes in the scope of work required of the subcontractors. According to information produced at the 1972 hearings, the cost of inflation to the subcontractors amounted to $141.8 million, and an increase of $187.9 million was attributed to the subcontractors' reduced business bases. In the opinion of the full Senate Armed Services Committee, GAC "seriously underestimated its subcontractor costs" (by approximately 50¢ on the dollar). As part of its $474 million bid reduction in January 1969, just prior to receiving the contract, GAC reduced its subcontractor estimates by $141.5 million to a total of $817.9 million. Yet, when GAC executed the actual contracts, the price increased to $1.1 billion, the $280 million overrun representing the difference.

Another major cost growth factor was the business base reduction at Grumman Aircraft Corporation corresponding to the general aerospace business recession experienced throughout the industry. Grumman's cost analysis of production Lots IV through VII reflected an estimated increase of $234 million attributed to reduced business base. Expressed in terms of millions of manhours, Table 5.3 presents the extent of the reduction in the business base at Grumman Corporation, historically and as projected. The anticipated 1969 estimated manpower base corresponded to a planned dollar volume of $1 billion annually. The

	1970	1971	1972	1973	1974	1975	1976	1977
1969 Estimate:	47.1	48.6	49.5	48.7	49.2	49.2	49.2	49.2
Current Estimates:	38.7	30.9	26.3	24.8	23.7	21.5	19.5	18.7
Estimated Decrease:	8.4	17.7	23.2	23.9	25.5	27.7	29.7	30.5
% of 1969 Plan:	(–)18.2	(–)36.4	(–)46.8	(–)49	(–)51.8	(–)56.4	(–)60.3	(–)61.8

Man-Hours in Millions

TABLE 5.3. GAC BUSINESS BASE

actual base was about half that figure. In spite of an intensive cost-control program, Grumman insists it is this loss in business base which primarily has caused them to refuse to produce the contracted aircraft in Lots V through VII at the agreed cost.

Grumman adds that their subcontractors' business reduction would necessitate an increase of about $282 million for Lots IV through VII.

GAC estimates that their total cost growth was divided approximately as follows:

Inflation - 28%
Base Reduction - 40%
Changes - 32%

These three primary problem areas all developed during the R&D phase and caused the Navy to transfer funds from production to R&D, thereby proportionately increasing the F-14 program unit cost.

A gross estimate of the R&D portion of the total F-14 program expense can be derived from the June 30, 1970 and June 30, 1971 entries in Table 5.2. Learning-curve experience shows that doubling the production quantity reduces unit cost about 20% in the mid-curve region. Let us assume that the planned R&D costs (X) are the same for both programs and that the 722 production unit cost per aircraft (Y) is 80% of that for the 313 aircraft program. Solving a simple simultaneous pair of linear equations:

$$X + 722\ (0.8Y) = \$8.3 \text{ billion}$$

$$X + 313Y = \$5.2 \text{ billion}$$

yields the result that the gross R&D program cost is $1.52 billion with a 313 aircraft production cost per airplane of $11.7 million. The 1972 R&D F-14 program cost was estimated to be $1.463 billion, with a production unit cost of $12.6 million. We conclude our simple calculations are essentially substantiated: the controversial increase in F-14 program unit cost is largely due to decreased total production quantities: to keep the program within the same total budget, the increased R&D costs dictated a reduction in the production quantity.

The growth in R&D costs was particularly well illustrated in the F-14 program review presented by its then Program Manager, Captain Ames, USN, to the Tactical Airpower Subcommittee on April 23, 1971. Table 5.4 is abstracted from his presentation. It is interesting to contrast the original contract baseline costs with the Navy approved costs as of April 23, 1971. Thus, in 1969 the actual RDT&E cost was $174 million, a slight increase over the programmed $130 million figure. But in 1970, whereas the original baseline figure was $175 million, the actual RDT&E cost totalled $515 million, greater than planned by almost a factor of 3. The actual difference, $340 million, is a substantial part of GAC's $474 million last-minute bid reduction.

In 1971, the two figures were not extremely different; there was only a slight increase of $23 million. However, in 1972 the 1971 Navy program foresaw an increase from the original baseline RDT&E of $88 million to an actual $228 million, again an increase by a factor of almost 3. The 1972 difference is $140 million. Added to the 1971 R&D overrun, the total overrun is $480 million; almost exactly the amount of the original GAC bid reduction.

These figures are reflected in the total column of Table 5.3 which, including figures not presented for the years 1973 to 1978, show an original planned baseline contract RDT&E cost of $731 million, to be contrasted with a project cost of $1.393: representing a growth by a factor of 2, and again displaying a difference close to the original $474 million bid reduction.

The 1972 Congressional hearings listed this $731 million as R&D for the F-14A alone, and added another $243 million as R&D for the F-14B, yielding a total planned R&D expense of $974 million. However, the R&D budget for the entire R&D program was then raised to $1.463 billion, for a net growth of $489 million in R&D funds over the original estimate. Once again we see the similarity to the original $474 million bid reduction. Whichever set of figures is employed, there can be no doubt but that the F-14 cost growth occurred primarily in its early R&D phase and amounts to about the same total figure as the original bid reduction.

Also apparent from Table 5.4 is the fact that funds were transferred from Procurement, that is PAMN, to RDT&E to fund the increased R&D costs. That transfer is brought out by

	FISCAL YEAR					
	1969	1970	1971	1972		TOTAL (1969-1978)
ORIGINAL CONTRACT BASELINE						
Quantity:						
R.D.T.&E.	6					6
PAMN		6	30	96		463
Total						469
Cost:	Millions of Dollars					
R.D.T.&E.	130	175	314	88	D	731
PAMN		275	783	1,103		5,192
Total Cost	130	450	1,097	1,191	E	5,923
					L	
CURRENT NAVY APPROVED					E	
Quantity:						
R.D.T.&E.	6	6			T	12
PAMN			26	48	E	710
Total					D	722
Cost:						
R.D.T.&E. F-14A:	Millions of Dollars					
Lot I	142	195	274	128		803
Lot II		266				266
F-14B	32	54	63	100		324
Total	174	515	337	228		1,393
PAMN		18	658	806		6,979
Total Cost						9,372
						(millions of dollars)

TABLE 5.4
F-14 PROGRAM REVIEW - APRIL 23, 1971

contrasting the funds originally scheduled for PAMN and those actually employed by the Navy. Thus, in 1970 a planned $275 million PAMN cost is to be contrasted with an actual $18 million expended. In 1972 a planned $1.1 billion is to be contrasted with an approved $806 million. The arbitrary transfer of funds from procurement to R&D is illegal. The actual mechanism employed to account for this shift was to redesignate as R&D expense the first half-dozen aircraft originally scheduled for procurement funding.

The same R&D overrun is further evidenced by comparing the January 1, 1969 Development Concept Paper (DCP) Production and R&D cost estimates with those of the December 31, 1971 Selected Acquisition Report (SAR) for the F-14 in Table 5.5:

TABLE 5.5

	DCP 1/13/69	SAR 12/31/71
Production (A/C)	$5.192 billion	$3.805 billion
RDT&E Total	$ .974 billion	$1.463 billion

The R&D budget grew 50% ($489 million, again close to $474 million) while production was cut 25%. It was the reprogramming of funds from Production to R&D, together with the resulting cutback in actual numbers of aircraft to be produced, which is reflected in the high program unit-cost of the F-14 aircraft program.

Confusion often arises among the three types of unit costs. One, the so-called "fly-away" unit cost, is the (average) production cost of the airplane alone. It does not include spares or other support costs. When these are added, the result is the "procurement" (or sometimes, production) unit cost. When all costs -- including R&D, production, and support -- are divided by the total number of aircraft produced, the result is the "program" unit cost.

To illustrate the typical differences among the three unit costs, the October 1972 figures for both the Air Force F-15 and the Navy F-14 are as follows in Table 5.6:

TABLE 5.6

	Fly-Away Cost	Production Cost	Program Cost
F-14	$9.4 million	$12.6 million	$16.8 million
F-15	$7.5 million	$ 9.75 million	$13.5 million

The F-14 is larger and has more complex avionics than the F-15, primarily because it is designed to carry and control the six 1,000-pound Phoenix missiles, and because it must operate from aircraft carriers. This capability also accounts for much of the extra cost of the F-14 in comparison with the F-15. However, if the same learning curve approach employed earlier were applied to these October 1972 figures, it can be shown that the unit costs of the F-15 and F-14 would be almost identical for the same total production. Thus, if the planned F-15 buy of some 700 planes were halved, the unit fly-away cost of the F-15 would rise to approximately $9.4 million, precisely the cost of the F-14.

When it is appreciated that the F-14 is a larger plane, has a longer range, and is capable of launching and controlling the Phoenix missile, we see the F-14 is potentially a better buy than the F-15. The F-14 swing-wing, which the F-15 lacks, would give the Tomcat better maneuverability. The F-15, being lighter, would have better acceleration; but the top speeds of the two airplanes are nearly the same, being limited by the heat barrier. The F-14 could undertake all the F-15 missions, have a greater range, and carry the Phoenix missile as well (which the F-15 cannot). The DoD should consider replacing the F-15 with the F-14, which it could do for essentially the same unit cost, given the resulting increased F-14 production quantities. A careful comparison of the two aircraft by DoD in the various Navy and Air Force missions is called for. The comparison should include actual fly-off trials as well as analytical studies. Substantial DoD savings could result from using one airplane in place of two which are so similar.

Of key importance in such a comparison is the Phoenix missile. The Phoenix program began in December 1962, with a total investment of $1.098 billion to 1972. The associated AWG-9 program has cost $750 million since 1962, with the unit cost holding at $2.022 million in 1972. The combined AIM-54/ AWG-9 programs account for approximately 25% of the total F-14 program costs. The Phoenix missile system requirements are responsible in large measure for the fact that the F-14 is the most expensive fighter plane in the world today.

The Phoenix system also accounts for an unprecedented "all-up" weapon system cost for any fighter airplane. Six missiles and the AWG-9 totals $3,666,000 per plane. Each Phoenix missile costs about 1/4 million dollars. The Phoenix demands its own cost analysis.

In summary, the F-14 cost history illustrates four primary pricing problems which confront every prospective military aerospace contractor: questionable initial estimates and the possibility of competitor buy-in; runaway inflation; and economic recession with its associated reduced business base. As corresponding solutions, the following are offered:

1. The Navy should employ its own parametric cost estimates as guides for contractor selection. Navy negotiator teams, combining technical and cost specialists, should be responsible for identifying probable buy-ins. The Navy should replace its former position of procuring the most favorable terms for the Government, regardless of circumstances, by a policy of combining price realism and equitable terms of contract with good technical judgment.

2. Incorporation of realistic inflation estimates, based on the best current projections of the Bureau of Labor Statistics, should be mandatory in all contracted future pricing. All potential contractors should employ the same inflation indices, as predetermined by the Government for the specific contract. Better yet, dollar payments should be adjusted to reflect inflation, actually and experienced.

3. The Government should never have to renegotiate fixed price contracts because of higher overhead

rates due to business base erosion. To do so with large aerospace contractors because of "bigness" would be unfair to all the other, not quite so big, businesses with which DoD has contracted during the last few years of recession in the R&D business. It should be recognized, however, that such an increase in overhead can comprise two different types of expenditure. (As used in similar discussions, the term "overhead" here is taken in the generic sense, i.e., including general and administrative expenses, rather than in the strict technical sense.) Some increased overhead rates are due to the company's failure to reduce "indirect labor" personnel when the direct labor base is reduced. Any encouragement of this attitude is dangerous, as it would tend to stop any motivation on the part of industry to remain efficient. Another part of increased overhead may be that due to the idle plant or engineering space which, when owned by the company, create an item equivalent to a cost in their "depreciation." Here, a willingness on the part of the Government to renegotiate overhead upward would again remove any motivation on the part of contractors to convert to other activities. If, however, conversion of a contractor-owned facility to a non-defense activity is considered undesirable by the Government, separate contracts could be entered into, which in the form of rent or payment for option to use, would motivate the contractor to keep a facility idle, ready for reactivation.

Let us examine the facts which could lead to contract renegotiation. First, we should admit that in fact, the billings on contracts, whether they be fixed price or CPFF, are always renegotiated in practice. The reason for such renegotiations are varied, but generally center around engineering changes that appear necessary while the equipment is under development for manufacturing, or the need for additional R&D to be performed on the systems or one of the major subsystems, or (in the case of CPFF contracts) simply because an overhead adjustment is warranted. Some major aerospace or defense contractors have unique facilities that are worth preserving as a national resource. It has also been said that the teams that are associated with these facilities must be preserved with their capability intact in the specialty in which they have always functioned. National policy now dictates a general reduction in the aerospace industry facilities and staff. However, there is a general consensus that the Government should attempt to help certain firms convert themselves to other activities. As the dollar value that can be generated by Government contracts outside the defense field is extremely limited, the problem becomes one of motivating firms and their management into a conversion that will still meet the goals of keeping certain essential facilities and the central teams available for possible important national security tasks of the future.

Any solution to the problem must take into account the fact that Government must provide an equitable solution acceptable to all. Many approaches to this problem have been proposed. We shall discuss here only those that have been the most actively publicized.

The solution generally advocated by the contractors is that the Government should agree to renegotiate contracts and pay the increased overhead due to a decrease in their business base. We shall use the term "overhead" here as it has been used many times in discussions with the public at large in the sense of all the indirect expenditures, including what is technically called overhead and general and administrative expenses.

The figures can be clarified somewhat by breaking out the increased overhead due to the company's keeping nondirect labor personnel on the payroll, even though they may have made a reduction in the direct labor base.

Another common overhead factor may be the vital plant or engineering space rendered unoccupied by a reduction in business base. This increased overhead charge is due to the depreciation of plant or engineering space, which is not used in the performance of a contract.

Those who advocate the reimbursement of this type of increased overhead argue adherence to the principle that Government must be equitable to all in business, and that contractors doing business with the Government are entitled to reimbursement of their costs. Those who are against such reimbursement or renegotiation envision an action which will remove from the contractor the motivation to either reduce his indirect labor staff in proportion to his direct labor base (which is considered a sound business practice), or a motivation to keep idle a facility which could possibly have been reconverted to another type of industrial activity. A case might be made for keeping a plant idle for one or several years if it is anticipated that it will be used again one day. However, the protagonists of the "tough line" see in this action only a way of postponing the painful moment when reconversion is inevitable.

A possible solution to the problem would be for the Government to give contractors a rent, or make periodic payments to have an option to use a certain amount of plant space. In this manner, plants and equipment can be "mothballed" at a cost that would approximate the depreciation on the contractor's balance sheet. In a sense, this system is comparable to the soil bank which was utilized to solve some of the problems of overproductive capacity of the agricultural segment of the economy. It would have some disadvantages in that the taxpayers' funds would be used on non-productive tasks, and it would also tend to decrease the aggressiveness of industry simply due to the fact that having an idle facility would not be as penalizing as it is today.

Finally, the Government could give design or study contracts to keep together those teams which they consider essential. Such contracts should be funded on the basis of reimbursing actual costs but with no fee. This formula would have the disadvantage that certain contractors would be favored by essentially obtaining the contract to write the subsequent procurement proposal.

Another possibility would be [illegible] allow matters to reach a desperate state, and then have the U.S. Government provide a guaranteed loan. This approach has the advantage of simplicity in that only one action is required by the Government, and that no renegotiation of a number of contracts must be entered into. However, it has several great disadvantages. First of all, it tends to favor big business, or as has been said several times, rewards poor management. It should also motivate contractors in the wrong direction. Let us assume, for instance, that a company is getting into difficulties due either to poor commercial business or refusal of the Government to pay higher overhead expenses. This company could be tempted to gradually sell its operating profitable divisions to other major defense contractors so that the work is continued without a disruption of management at the operating level, and enough cash is raised to keep the rest of the corporation going or to reconvert it. The knowledge that the Government guarantees loans could motivate the contractor to keep the operation going toward disaster, and then request help just at the time when such disaster is imminent, thus being able to state that everything will cease, even programs vital to the national defense, unless a loan is made available.

The reaction of the U.S. public to the F-14 aircraft and the controversies which have surrounded the discussions between the Navy and the contractor concerning renegotiations have certainly been out of proportion to the actual magnitude of either the additional delay or the cost growth incurred during the program, when it is viewed in comparison with other recent major weapon procurements. The public has been sensitized to cost overruns, in particular by the C-5A. It will be extremely difficult to obtain a consensus of the voting public on the need for renegotiating any complex, expensive weapon systems in the future.

VI. SYSTEMS ANALYSIS

According to Grumman, the three primary factors which account for the growth in F-14 costs subsequent to the award of the GAC contract in February 1969 are:

1. Inflation (28%);
2. Business base erosion (40%);
3. Contractor initiated change orders (32%).

Whereas a particular corporation's business base usually reflects the general state of the economy to some degree, overhead still remains under control of the contractor. The particular circumstances at GAC were discussed in the previous chapter. Further analysis would require detailed investigations at GAC beyond the scope of this study. Contractor initiated changes reflect unforeseen R&D problems as well as poor initial estimates, bad technical planning, and questionable project management. The latter three should be under the control of the prime contractor. It is the very nature of R&D to develop unforeseen problems. Financially, they are handled by contingency funding and cost-plus-fixed-fee contractual arrangements. Therefore, of the three growth factors, only the first -- inflation -- lies entirely outside the control of the contractor. Let us look more deeply into the role of inflation in the cost growth of fighter aircraft as our first systems analysis effort.

Inflation affects both the "natural" cost growth which occurs between successive generations of aircraft -- for example, between the F-4 and the F-14 -- and also the growth in cost after the award of a contract. There are various possible measures of inflation. The most common is the Consumer Price Index, maintained by the U.S. Department of Labor, Bureau of Labor Statistics. Table 6.1 is reproduced from that source. The scale of Table 6.1 is arbitrary, corresponding to a value of 100 in the latter part of 1957. These indices are also plotted in Figure 6. for the years shown. From Figure 6.1 we see that, historically, the value of the dollar has shrunk so that an article which would have cost $.92 in 1952, would have cost $1.45 in 1972.

It is often more informative to consider the incremental change in inflation from year to year. Figure 6.2 presents that percent annual inflation change between successive years from 1955 to 1971. It is interesting to observe the rapid

YEAR	
1939	48.4
1940	48.8
1941	51.3
1942	56.8
1943	60.3
1944	61.3
1945	62.7
1946	68.0
1947	77.8
1948	83.8
1949	83.0
1950	83.8
1951	90.5
1952	92.5
1953	93.2
1954	93.6
1955	93.3
1956	94.7
1957	98.0
1958	100.7
1959	101.5
1960	103.1
1961	104.2
1962	105.4
1963	106.7
1964	108.1
1965	109.9
1966	113.1
1967	116.3
1968	121.2
1969	128.0
1970	139.8
1971	141.8
1972	145.2

Source: Bureau of Labor Statistics,

Wall Street Journal

TABLE 6.1. CONSUMER PRICE INDEX

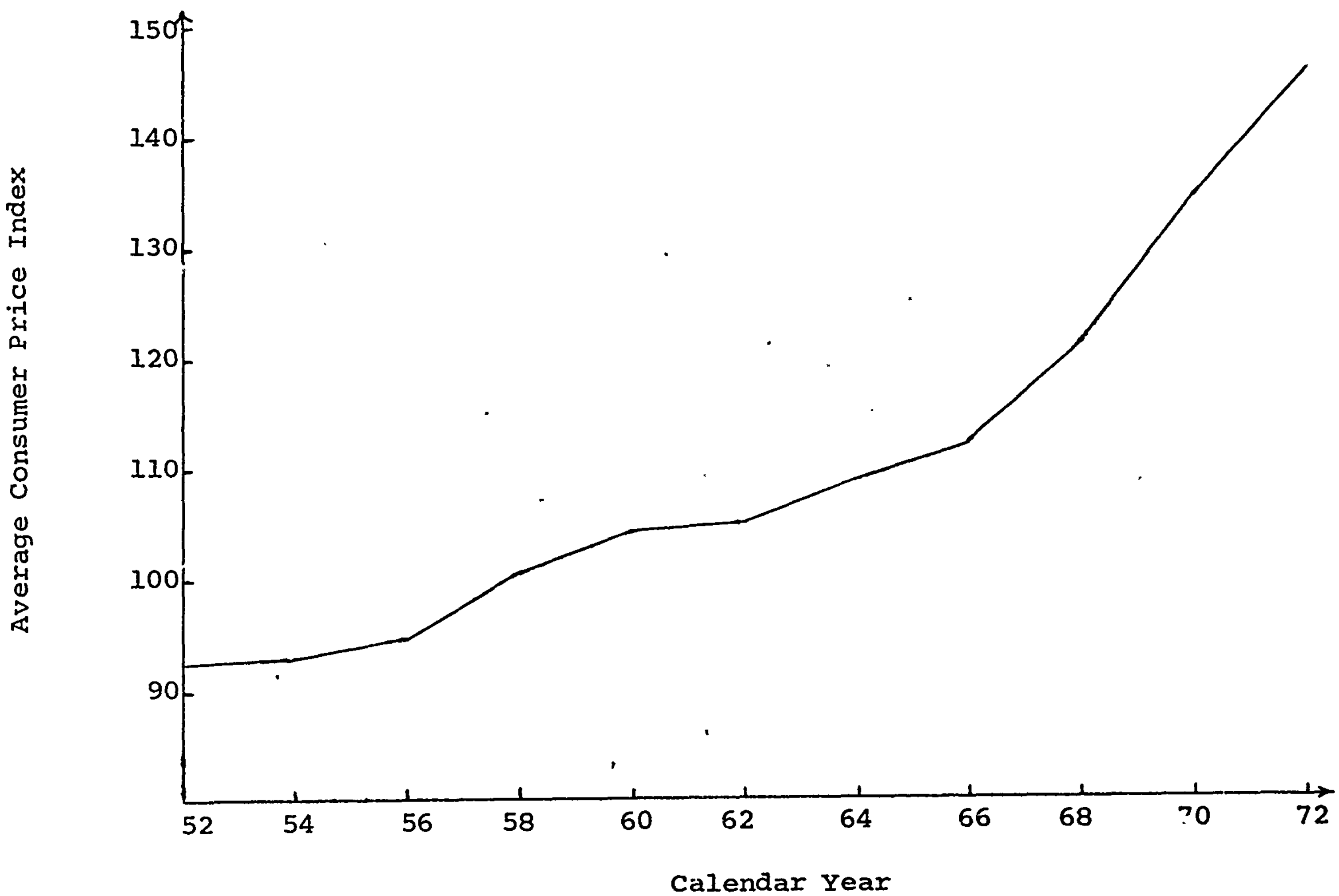


FIGURE 6.1: CUMULATIVE INFLATION AS DEPICTED BY CONSUMER PRICE INDEX

(Source: Bureau of Labor Statistics)

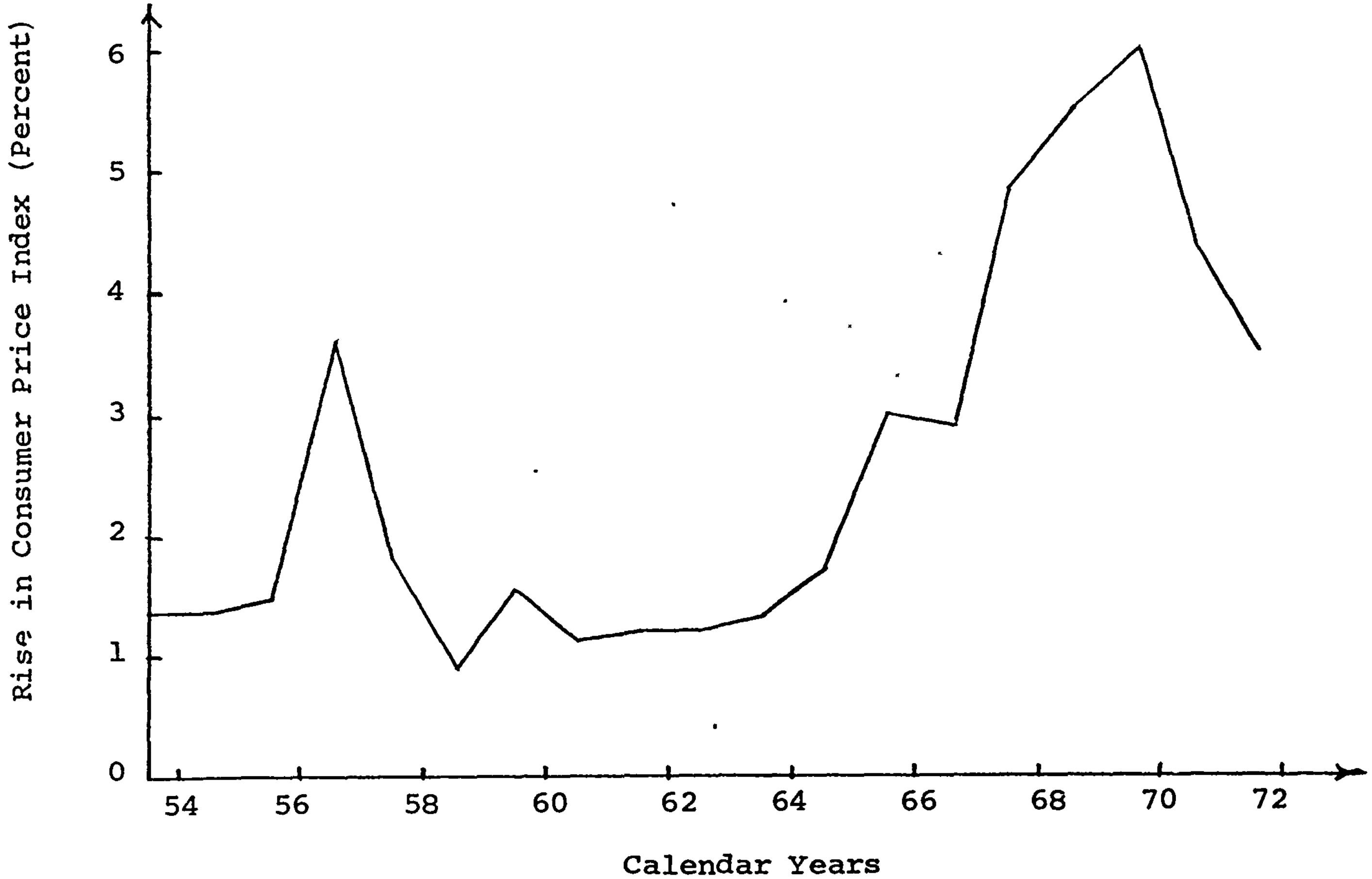


FIGURE 6.2: PERCENT CHANGE IN INFLATION BETWEEN SUCCESSIVE CALENDAR YEARS

(Source: Bureau of Labor Stat.)

increase in inflation from 1964 to 1970. The reader will recall that it was during this period that Grumman Corporation estimated its future annual labor rate of inflation would be 3%, and material inflation rate, 2%. Reading from the graph, a more viable combined figure would have been nearer 6%. However, the Grumman Corporation, it will be reaclled, justified its selection on the basis of the average for the preceding 10 years, which they stated to be about 3%. Calculations of cumulative inflation employing the data of Figure 6.1 indicate that inflation in the U.S. had been growing at an average rate of 3.1% annually since 1940. The average rate of growth since 1950 has been 2.9%; whereas the 10-year rate of growth of inflation prior to 1969 was 3½%. There is good reason to believe that the average rate of increase in inflation in the U.S. historically has been approximately 3% per year; however, Grumman should have chosen a short-term projection, not the long-term average.

When contrasting the F-4 and F-14 costs, a common uninflated dollar should be employed. If we take the first production model of the F-4 to have appeared in 1959 -- that is, if we take 1959 as our baseline year -- we find that a cumulative inflation of approximately 45% was experienced through the end of 1972. This means that the early-production fly-away cost of F-4B, which was approximately $4 million in 1959, would be the equivalent of $5.8 million in 1972. Thus, the anticipated fly-away cost of the F-14 is only about twice that of the F-4 when both are measured in 1972 dollars (without inclusion of weapon systems, spares, and similar costs). If the comparison were made with an earlier date -- say 1955, when the F-4 was first begun -- the cumulative price index would have increased 58%. What would have cost $1.00 in 1955 would cost $1.58 in 1972. The corresponding cost of the F-4 would be about $6.4 million. We see, therefore, that inflation is indeed a major factor in comparing costs of different aircraft built in substantially different time frames, and that a large part of the F-14 cost growth over the F-4 may be attributed to inflation.

Furthermore, since 1969 when the Grumman contract was signed, the cumulative price index has grown by 20%, which means that what would have cost $1.00 in 1969 now costs $1.20: a substantial increase caused by inflation subsequent to the signing of the contract by Grumman in February 1969.

It is apparent that even when inflation is included in one's calculations, the F-14 still costs about twice as much as an F-4 would cost were it built today. What accounts for this additional cost -- what we have called the "natural" growth -- between successive generations of fighter aircraft? The obvious, and we believe correct, answer is that this natural growth primarily reflects technical change: increased complexity or sophistication. Thus, whereas the F-4 and the F-14 are about the same size, carry approximately the same weapons (except for the Phoenix), and are designed for the same missions, the F-14 has incorporated many technical advances not embodied in the F-4. The primary ones are: the inclusion of the turbofan engine; more extensive use of titanium; inclusion of the swing-wing; and most particularly, provision for the Phoenix missile with its associated electronic AWG-9 fire control system. The F-14 avionics particularly are far more complex than those of the F-4. (Indeed, as noted in the cost analysis, the all-up cost of six Phoenix missiles and the AWG-9 totals $3.3 million per aircraft.) The problem with identifying cost increases between successive generations of fighter aircraft as resulting from technical change is that the effect of managerial inefficiency -- particularly of poor cost control -- is not considered. The two are difficult to separate.

The McDonnell Douglas Corporation recently conducted a study in which they tried to estimate what the F-4 production learning curve costs would look like if the F-4 were produced today, using the current, more modern production techniques and equipment. They estimated F-4 production costs on the assumption that the F-4 was to be procured on the present F-15 schedule. Their result is depicted in Figure 6.3. Instead of the overall growth factor of 1.6, representing the effect of inflation between 1955 and 1972, a factor of nearly 2.5 is required. Therefore, an F-4 which sold for $4 million in 1955 would sell today for $10 million, according to this study. We can ascribe part of the difference to increased management costs. The factor 2.5 corresponds to an average (exponentially compounded) annual growth rate of about 5.5%. Thus, increasing production complexity due to meeting diverse requirements of many different customers accounts for about an average 2.5% annual increase in fighter production costs after removal of inflation effects, according to this internal McDonnell study.

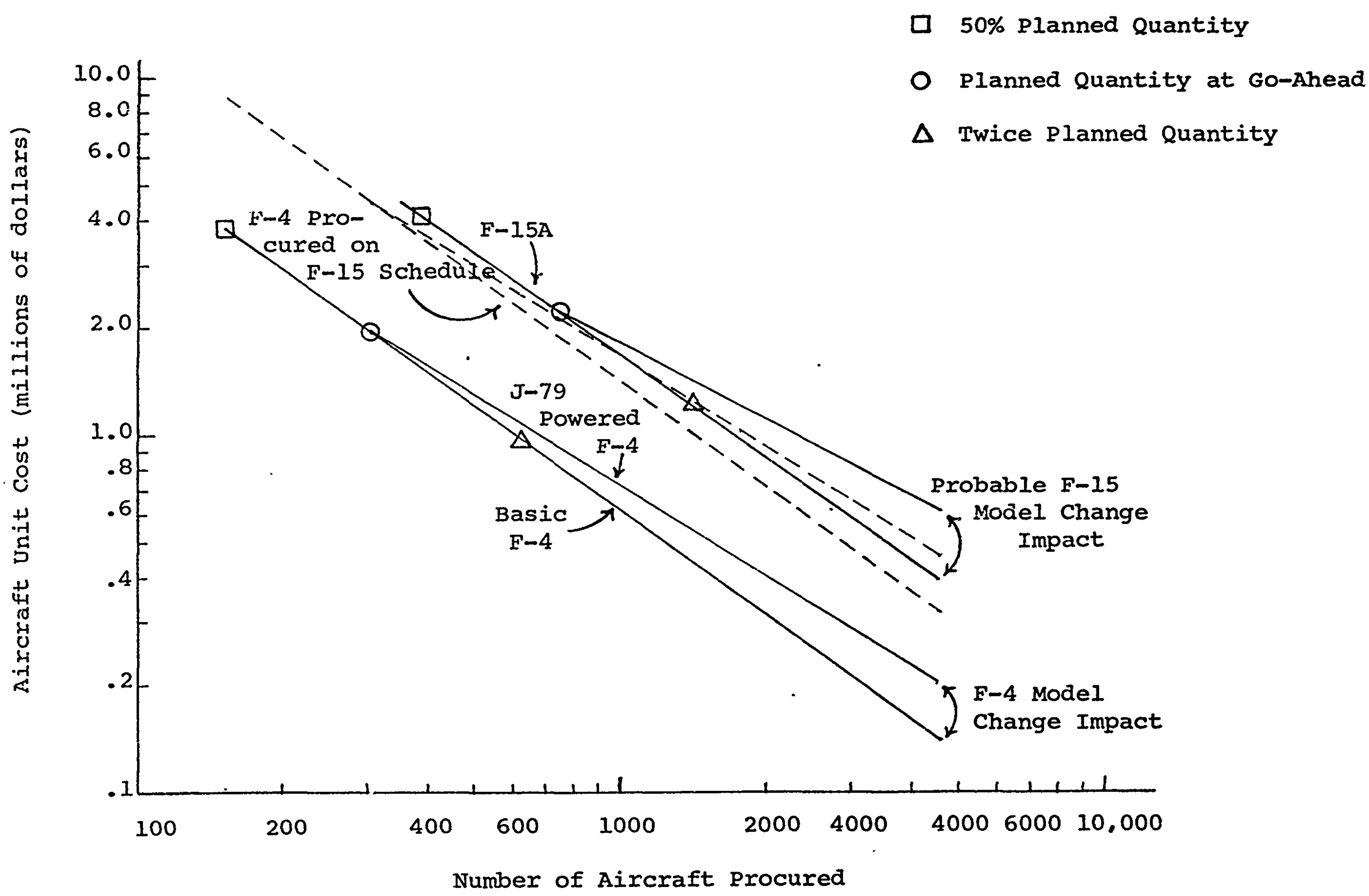


FIGURE 6.3: IMPACT ON PRODUCTION COST OF MODEL CHANGES IN F-4 AND F-15 AIRCRAFT

(Source: McDonnell Douglas Corp.)

We shall have more to say about the effect of technical sophistication on costs in the following regression analysis section.

From a more general viewpoint, it would seem reasonable to expect that the unit fly-away cost of fighter aircraft should increase over the years, reflecting their correspondingly increased technical complexity and sophistication. It would be useful if we could gain a measure of that increase.

The obvious way, used by economists, to measure such increases is to analyze historical data of similar systems; in our case, of fighter aircraft. We have undertaken ıch a regression or parametric analysis, using information from a variety of unclassified sources, including Jane's <u>All the World's Aircraft</u>, certain publications from the Naval Air Systems Command, and the May 1967 issue of <u>Astronautics and Aeronautics</u>. There is a problem in that the cost figures are representative of the various aircraft at different periods during their development. We have tried to use average fly-away costs, but the aircraft have had different production quantities. The average fly-away cost of an aircraft of 4,000 units total production would obviously be decreased by its learning curve over the average cost of an aircraft which had been cancelled after only 200 or 300 copies.

The particular regression calculation reflects cost growth (taken as unit fly-away cost) as a function of aircraft year of initial production. The particular points are plotted in Figure 6.4. A General Electric Mark I time-sharing linear regression program was employed to fit the upper line through the graphed points, representing the various aircraft fly-away costs.

The program input data and resulting printout are reproduced in Appendix I. The G.E. computer program is written in Basic programming language, and calculates the regression of the natural logarithm of the unit fly-away cost as a function of calendar years from 1946 to 1974. The regression line is the top straight line of Figure 6.4. The regression equation is:

$$\text{Log}_{10}(\$) = -3.45 + .060t$$

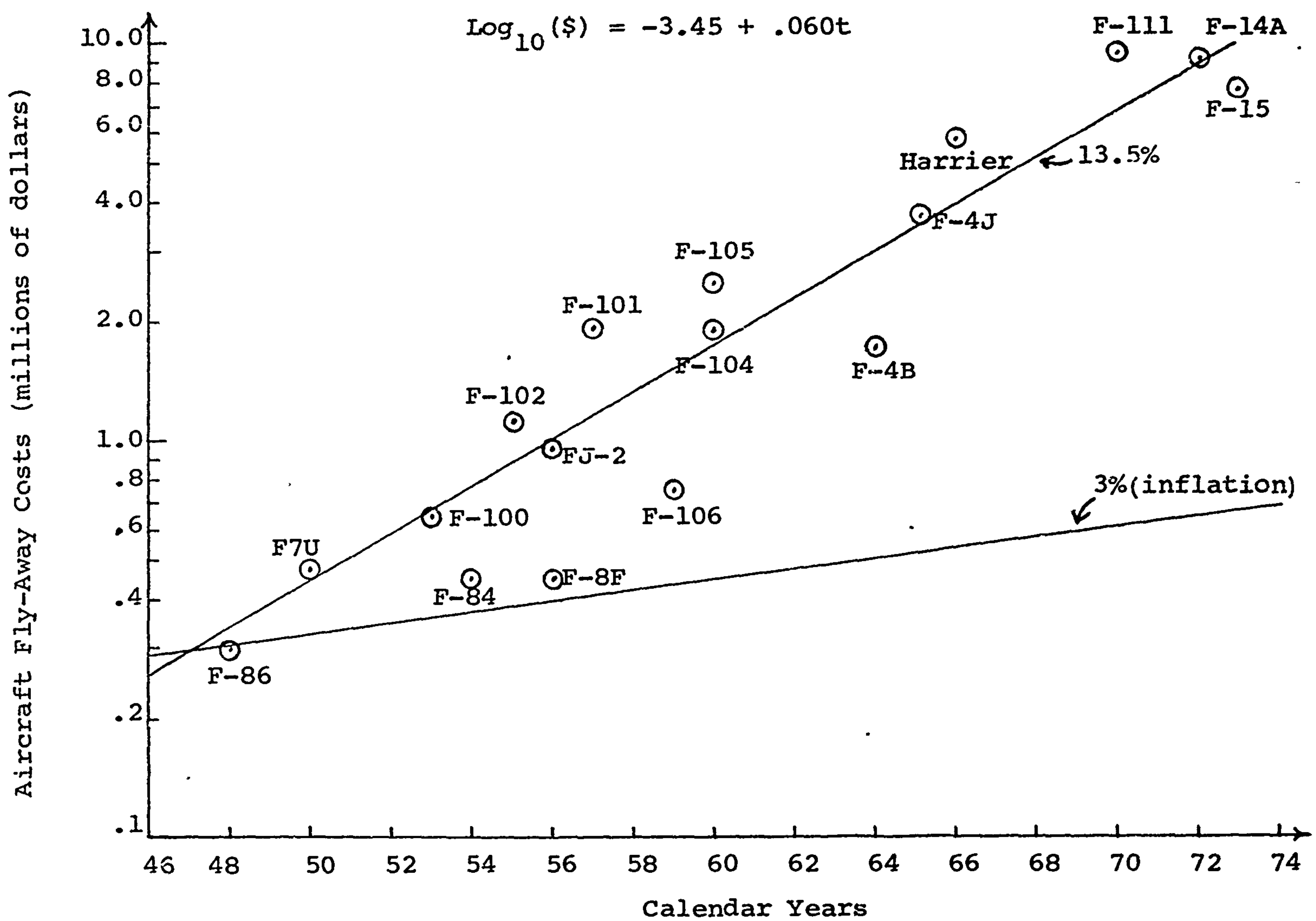


FIGURE 6.4: GROWTH OF AIRCRAFT FLY-AWAY UNIT COSTS

The regression coefficients are the equivalent of those calculated by the G. E. Mark I program when transformed from natural logarithms to logarithms to the base 10. As will be observed from Appendix I, the index of determination -- that is, the square of the correlation coefficient -- is quite good, as is the F ratio test statistic. The latter, 116.393, for the degrees of freedom of regression and error indicated on Appendix I, corresponds to a confidence level considerably greater than 99%. Thus, the regression calculation is reliable. (When reading the actual and calculated figures at the end of Appendix I, it should be borne in mind that they refer to natural logarithms, not logarithms to the base 10, as plotted on Figure 6.4.)

If we compute the average growth rate, that is, the slope of the regression line of Figure 6.4, we discover an annual rate of "technical growth plus inflation" equal to 13.5%. That is, the combined effect of technical sophistication and economic inflation represents an historical annual rate of growth in cost of fighter aircraft of 13.5%. If we subtract the historical average inflation rate of 3% -- which, incidentally, is also plotted in Figure 6.4 -- we obtain the result that technical complexity and/or sophistication have resulted in about an average 10% annual growth in unit fly-away costs of fighter aircraft from 1946 to 1974.

If we accept the McDonnell Douglas analysis of the F-4 production vis a vis the F-15, discussed on page 62, then 5.5% of this 10% growth corresponds to the effect of technical changes. The remaining 4.5% growth might be identified with management cost, as mentioned before. However, historically we can only say 10% is the average annual growth between successive generations of fighter aircraft, and that probably technical changes account for the major part of that 10% growth. A more careful analysis is required.

William B. Graham of the RAND Corporation published an article in the May 1972 Astronautics and Aeronautics, in which he plotted military aircraft and tank costs from 1920 to 1980. That figure is reproduced here as Figure 6.5. The regression line he shows for fighter aircraft represents an effective combined technical and inflation growth rate of 12.5%. A similar calculation was made for tanks. The resulting curve, also plotted on Figure 6.5, shows that U.S. tanks display an

MILITARY AIRCRAFT AND TANK COSTS

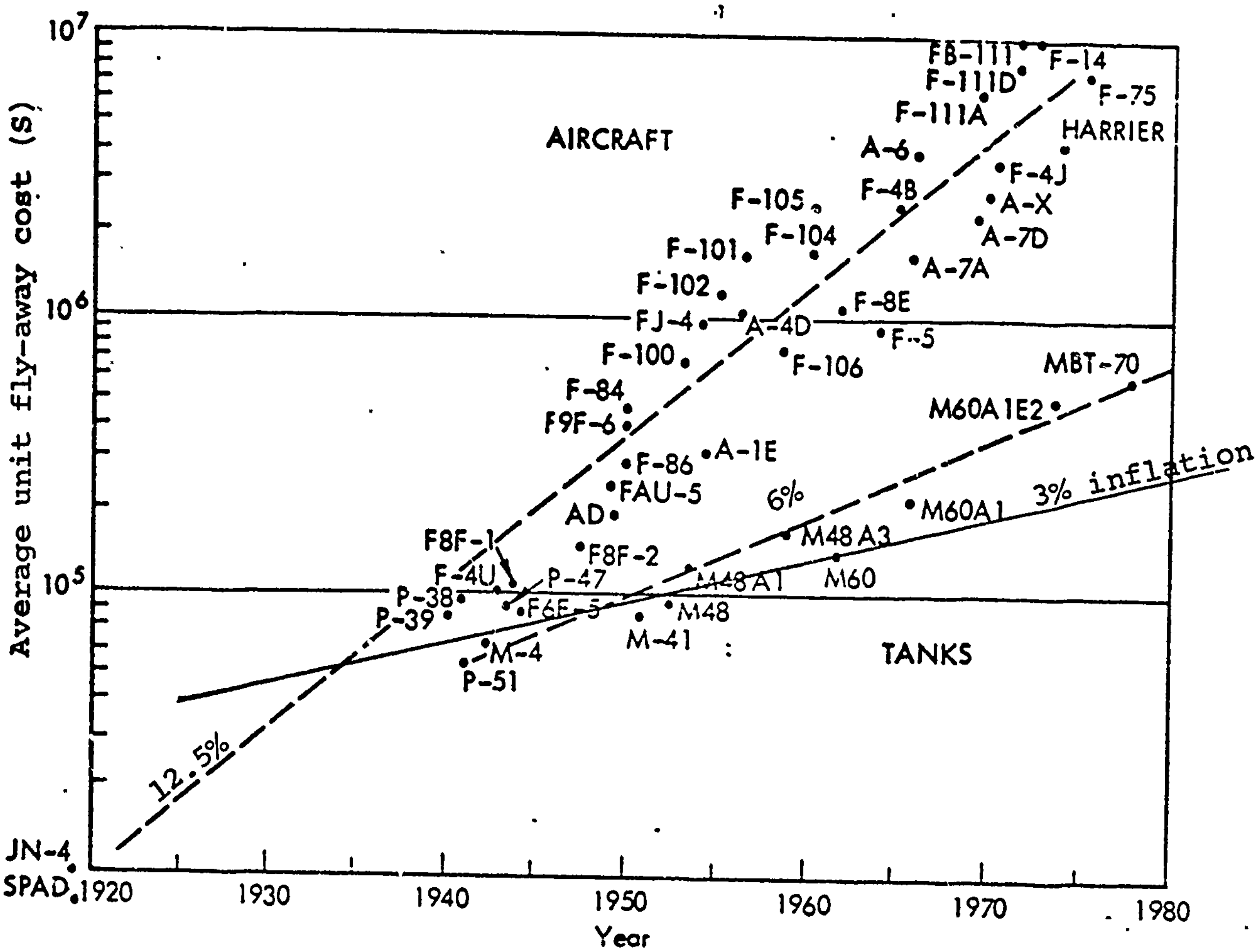


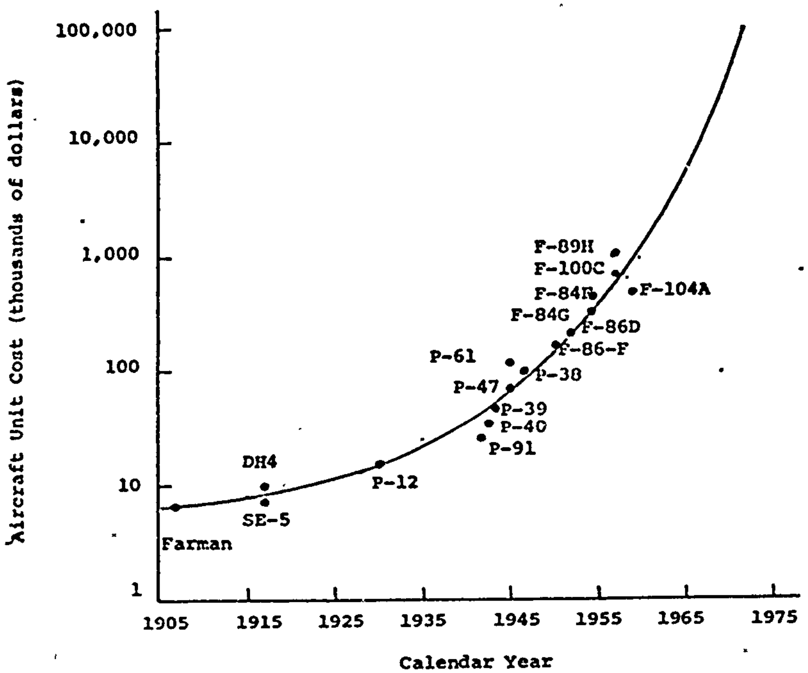
FIGURE 6.5. MILITARY AIRCRAFT AND TANK COSTS

(Source: Astronautics & Aeronautics, May, 1972) historic technical cost-growth of about 3% per year, corresponding to the 10% figure for fighter aircraft. As tanks are technically less sophisticated than aircraft, the lower rate is appropriate.

Graham's analysis leading to Figure 6.5 was challenged by William Squire of West Virginia University, who called attention to H. K. Weiss' fighter/interceptor cost growth curve published in Air, Space, and Instruments in 1963. In answer, Graham plotted the Weiss curve and showed that it did not fit more recent cost data. Figure 6.6, reproduced from the August 1972 Astronautics and Aeronautics, shows recent costs for fighter aircraft fall far below the Weiss curve. Indeed, if the Weiss curve were satisfied, the F-111 would have cost $100 million, rather than its actual $10 million.

Graham decided that perhaps there were actually three cost regimes where linear regression lines would fit the data. He identified these as the period prior to 1945, the period between 1945 and 1960, and the period subsequent to 1960. But, as Graham himself noted, these aircraft cost data "do not conform to requirements for a stationary time series; that is, the underlying phenomena at work are not independent of time or aircraft." It is our judgment that one simple linear regression is adequate for the purpose of demonstrating the effect of increasing technical sophistication upon historical weapon systems costs.

All of the many objections to the F-14 voiced by its various critics really come down to one common criticism: in their view, $16.8 million is an excessive cost to pay for a single fighter airplane. A cost-performance justification is the only answer. Thus, the argument about the F-14 versus the F-4 must also come down to the question of cost-performance or cost-effectiveness. The F-14 critics maintain an F-4 with modifications, particularly wing flaps, could be given equal or greater maneuverability than the F-14. The F-14 proponents maintain that the F-14 performance is markedly superior, and that if the "B" engine were available, their plane would be so aerodynamically superior as to be beyond question. Our judgment is that the F-14 is, in fact, markedly superior. It should be, given the advantages of the sweep-wing and the turbofan engine, not to mention the weight reduction gained



Weiss' fighter-interceptor cost growth curve from Air, Space and Instruments, 1963, appears above. Graham has replotted it at the right, adding additional data shown in open circles. A new rate of cost growth which appears to apply after Weiss published is also shown.

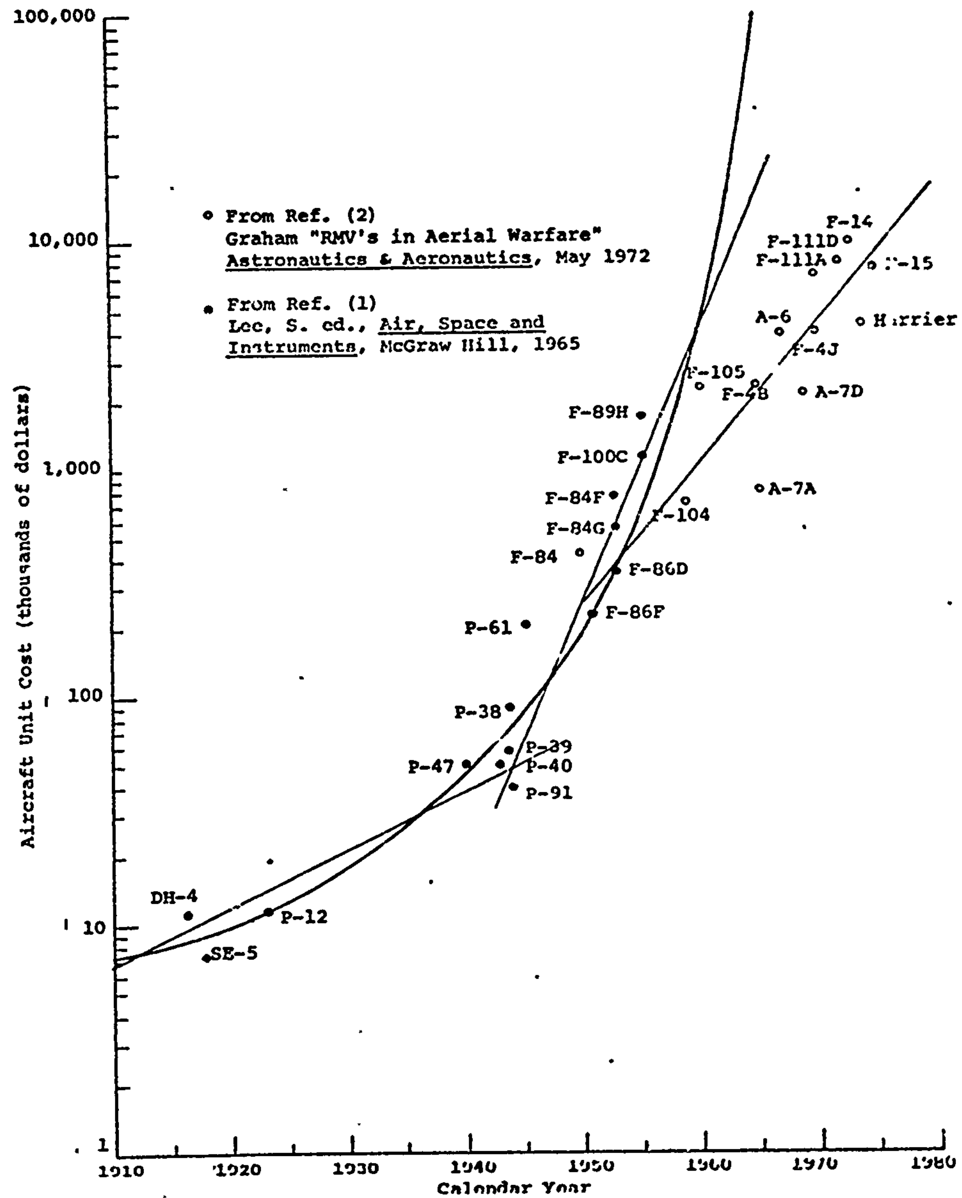


FIGURE 6.6. COMPARISON OF AIRCRAFT UNIT COST GROWTH RATE CURVES PREPARED BY WEISS AND GRAHAM

by the greater use of titanium. Nevertheless, the relative aerodynamic capabilities of the two aircraft may not be so great as to justify in themselves alone a unit-cost ratio of 2½ to 4. The two aircraft must be evaluated in comparison as weapon systems. Such a comparison, in detail, is well beyond the scope of this present study.

We have, however, devised a new approach to this question which we believe offers a simplified yet satisfying basis for comparison of the F-4 and the F-14, or indeed of any other two fighter aircraft with similar missions. The comparison we propose extends the now classic Lanchester equation by introducing cost concepts.

Lanchester, in his book, "Aircraft in Warfare,"(1) developed an equation which was designed expressly to answer the question as to the relative fighting effectiveness of a force of aircraft. The original purpose of Lanchester's now famous equation was to demonstrate quantitatively the advantages of force concentration; that is, the advantage of larger forces over smaller forces, other factors being the same.

The importance of concentrating forces has been recognized not only in the air, but on land and sea as well. In fact, Lanchester pointed out the advantages of the implicit use of his N^2 Law in the Battle of Trafalgar. The famous naval tactic known as crossing the T, in which a line of battleships perpendicularly crosses a line of enemy ships, really is employing the Lanchester N^2 Law to its advantage.

The derivation of the Lanchester equation is elementary. Basically, Lanchester assumed that the rate of destruction in battle of what he called the "blue forces" (b) is proportional to the numbers of the opposing enemy "red forces" (r), times their individual fighting value (N). In differential equation form, this relation is given by:

$$\frac{db}{dt} = -Nr \qquad (1)$$

Similarly, the "red forces" (r) experience an attrition rate given by the magnitude of the "blue forces" (b) times their fighting strength (M):

(1) Lanchester, F. W., "Aircraft in Warfare, the Dawn of the Fourth Arm," New York, Appleton, 1917.

$$\frac{dr}{dt} = -Mb \qquad (2)$$

The condition for equal opposing forces, that is, forces of equal fighting strength, is given by the equality of the percent reduction of the two forces. Expressed mathematically, this equality is given by:

$$\frac{db}{bdt} = \frac{dr}{rdt} \qquad (3)$$

Substitution of Equations (1) and (2) into Equation (3) yields the Lanchester equation:

$$Nr^2 = Mb^2 \qquad (4)$$

To repeat, in Equations (1) through (4), r and b are, respectively, the numerical strengths of the "red" and "blue" forces, and N and M are, respectively, their fighting values, to use Lanchester's term. In other words, Equation (4) -- which is the famous N^2 equation -- states that the fighting strengths of the two opposing forces are equal when the products of the square of the numerical strength multiplied by the fighting value of the individual units of both are equal. More generally, the Law may be stated as follows: "The fighting strength of a force may be broadly defined as proportional to the square of its numerical strength multiplied by the fighting value of its individual units."

Application of the Lanchester N^2 Law to a comparison of the F-4 and the F-14 requires the use of simplifying and far-reaching assumptions, without an analysis far beyond the scope of the present study. The necessary simplifying assumptions are the following:

1. We assume that the aerodynamic qualities of the F-4 and the F-14 are the same. We recognize that the F-14 is, in fact, superior. Thus, any differences will actually benefit the F-14 in subsequent comparison.

2. With the exception of the Phoenix missile, we also assume that the weapons carried by the two fighters are the same. This is, in fact, so. The planes employ the same weapons, and, in essence, the same numbers of those weapons, with the exception of the Phoenix missile.

Under these two assumptions, what Lanchester calls the "fighting value" of the individual F-4 and F-14 aircraft -- which would normally include such factors as maneuverability, speed, radius of action, armaments, rate of fire, etc. -- all reduce to a question of the effectiveness or advantage gained by the Phoenix missile, since all the other factors for purposes of argument have been assumed equal. Given the fact the F-14 actually has an aerodynamic advantage over the F-4, if it can be shown that it is cost-effective on the basis of the Phoenix missile alone, it then is surely even better in actuality.

What then does Lanchester's N^2 equation tell us? It says that two forces, one of F-4's and the other of F-14's, would be of equal fighting strength when the square of the numbers of the two forces, multiplied by their individual fighting values, are equal. Let us now introduce cost by stating that the two forces of F-4's and F-14's must be of equal cost. The number of aircraft, then, in each fighter force is given by the total force cost divided by the fighter unit cost. Letting C_r and C_b be the unit cost of the "red" and "blue" fighters, respectively, substitution into Equation (4) yields:

$$\frac{N}{M} = \left(\frac{C_r}{C_b}\right)^2 \qquad (5)$$

Equation (5) states that, if two forces of fighter aircraft are of equal fighting strength <u>and</u> of equal cost, then the ratio of the individual aircraft fighting values must equal the square of the ratio of their unit costs. Thus, if one fighter plane costs twice as much as another, then its individual fighting strength must be four times as great as the other's in order that a force of the first type be of equal total fighting strength to the second.

We shall for the moment omit the additional cost of the six Phoenix missiles from the analysis. Furthermore, let us compare the F-4 and the F-14 on the basis of their then-current year production unit costs, which we will take to be \$4 million for the F-4 and \$10 million for the F-14. We then ask, how much better must the fighting value of the individual F-14 be than that of the F-4 for the two forces of equal cost to be of equal fighting strength, that is, effectiveness?

For the two forces to be of equal cost, there will be 2.5 times as many F-4's as there are F-14's, since $2.5 = \frac{10}{4}$. This means that the fighting value of the individual F-14 must be $(2.5)^2$, or approximately six times that of the F-4, in order that the fighting strengths of the two forces be equal. With the simplifications we have made, this requirement resolves itself into the question of whether or not the Phoenix missile makes the F-14 six times better than the F-4 as a fighter system. The answer is: it does, if the Phoenix missile has unit kill probability. Six Phoenix missiles could be fired before the battle was even joined within the range of the F-4's missiles. Provided the Phoenix has unit kill capability, all six attacking F-4's would be destroyed before they came within range of their own weapons.

Now of course the Phoenix does not have unit kill probability, but then the actual cost comparison should be made in common year dollars. That in itself is easy enough, but what would the F-4 actually cost if begun today? No one really knows. We also have omitted the cost of the Phoenix missiles. Furthermore, the aerodynamic advantage possessed by the F-14 over the F-4 would itself compensate, or "trade-off", for a lower Phoenix kill probability.

The question of the cost-effectiveness of the F-14 vis-a-vis the F-4 thus becomes primarily a question of the effectiveness of the Phoenix missile. In a complete analysis, questions as to electronic countermeasures and the ability of a target to maneuver away from a Phoenix missile would enter; questions as to the reliability of the missile would enter; and questions of the Phoenix kill capability and multiple target capability would enter, etc. And, of course, we would need to include the cost of the Phoenix missiles, which was omitted previously to simplify the example.

If only the cost of the missiles was included, the higher F-14 unit cost would then not be justified. If we add the cost of six Phoenix missiles to that of the F-14 aircraft, we must add six times $250 thousand, or some $1.5 million for the missiles to the unit cost of the aircraft. The ratio for equal F-4/F-14 forces now becomes 11.5 to 4 squared, which is approximately 9. That is to say, if one includes the cost of a full complement of six Phoenix missiles, together with the fly-away cost of the F-14 aircraft, the fighting effectiveness of the Phoenix-equipped F-14 must be nine times greater than that of the F-4 similarly equipped except for the Phoenix missile. Now six Phoenix missiles are not enough to make up the difference in fighting value. The aerodynamic factors must be introduced, and the other simplifications removed before a satisfactory comparison can be made.

We recommend such an extension of this present Lanchester equation analysis to see whether or not we can actually justify the F-14 unit cost versus that of the F-4.

In a sense the F-14 plays a role vis-a-vis the F-4 similar to that which a cruiser plays to a destroyer: namely, the heavy guns of the cruiser outrange those of the destroyer. You need a large force of destroyers to counteract the range advantage given by the cruiser's guns. In essence, the F-14 is a "Cruiser" among fighter aircraft.

The F-14 is a combination Phoenix launch platform and conventional fighter. It is this multifunction characteristic of the F-14 -- together with its limited production -- which accounts for its high unit cost. If the F-14 were only a Phoenix launch platform -- a modern "Missileer," so to speak -- it could have far poorer aerodynamic capabilities and could be produced at a correspondingly lower cost. If it did not have the extra avionics, structural strength, and second pilot needed to carry and launch the six Phoenix missiles -- that is, if it were a more conventional modern fighter -- it would also cost less, probably less than the Air Force F-15. However, the F-14 combines the Phoenix launch platform and conventional fighter missions. It should and does cost more. In this sense, the F-14 really cannot be compared with the F-4, or any other current aircraft. The F-14/Phoenix combination is a new kind of air defense system. It is for this reason we suggest a more fitting designation would be F<u>M</u>-14, reflecting its Phoenix missile capability.

VII. SUMMARY

The F-14 is markedly superior to the F-4. It is faster, more maneuverable, has greater acceleration, and longer range. The F-14 gains these advantages through incorporation of three principal technical advantages: far greater use of titanium, markedly improving structural strength-to-weight ratios; new gas turbine turbofan power plants, offering significantly higher thrust-to-weight ratios and lower fuel consumption; and the variable geometry or swing-wing. The latter -- augmented by automatic sweep programming, maneuvering slats and flaps, and glove vanes -- affords the F-14 aerodynamic performance and, in particular, maneuverability, over a speed and altitude range unequalled by the F-4.

However, the present F-14 program unit cost of $16.8 million makes it the most expensive general purpose fighter plane in the world (neglecting the special-purpose A-11). Should Grumman Aerospace Corporation (GAC) be successful in its current attempts to renegotiate the price of production Lots V through VIII, the cost could grow to $18.6 million, further aggravating the plane's cost-conscious critics and correspondingly jeopardizing its future production.

The present study, conducted under ONR Contract No. N00014-C-72-0339, compares the F-14 with its predecessor, the F-4, and draws lessons which would guide the Navy in its future air superiority and fleet air defense fighter design and procurement. The study traces the development and history of the two aircraft; undertakes a cost analysis, primarily of the F-14; and pursues a systems analysis incorporating the effect of inflation and a new approach to a cost-effectiveness comparison of the two fighter planes. Three methodologies are employed in the study; historical analysis; parametric or regression cost analysis; and a novel extension of the classic Lanchester equations. A fourth, on prototyping, is not pertinent and is omitted from this report.

The primary mission of both the F-4 and the F-14 is fleet air defense. To satisfy DoD requirements for multi-purpose weapon systems capability, both the F-4 and the F-14 were also designed for the complementary air superiority role, and to permit ground attack as well. In the case of the F-14, these three capabilities are obtained through use of a unique pallet system which adapts the aircraft payload to specific mission requirements. The F-14 is intended to replace the older F-4.

The primary threat is the Soviet MIG-23 (now redesignated the MIG-25) or Foxbat. Although the Free World planes such as the F-15 can attack the Foxbat using short-range missiles and "jump-up" tactics, only the F-14 has the high kill probability to destroy the MIG-23 at maximum altitude and long range with the aid of the Phoenix missile and associated AWG-9 avionics.

The F-4 was a new design which evolved during prolonged negotiations between McDonnell Aerospace Corporation and the U.S. Navy. Formally, it was an unsolicited proposal, but actually it represented the fruit of the intimate relationship which then existed between McDonnell and the Navy.

That same kind of intimate relationship existed between the Navy and GAC. However, the imposition of the novel McNamara R&D procurement procedures, such as Concept Formulation and Contract Definition, required arm's length negotiations which hampered the formerly close Navy/GAC informal cooperation. The Navy had been working with GAC in developing the ill-fated F111-B. When it became apparent the F111-B's weight -- resulting from a combination of swing-wing structure, aircraft carrier landing, and Phoenix-carrying requirements -- would prevent its use aboard aircraft carriers, the Navy turned to GAC to study a possible replacement (the VFX).

Charges of favoritism and even collusion have resulted from that latter GAC/Navy association. The known facts can be summarized as follows. The Navy let a million-dollar-plus contract in 1964 to GAC to study the possibility of a successor to the F111-B. GAC, a subcontractor to Convair, was responsible for the F111-B. The Navy awarded the F-14 prime contract to GAC after a competition in which GAC submitted only the third lowest of five competing bids. However, shortly before the award in February 1969, GAC reduced its bid by $474 million from an original figure of $2.894 billion. The Navy's independent estimate had been $2.893 billion. Although the GAC bid was still $100 million higher than McDonnell's (the other finalist), the Navy selected the Grumman design because of genuine technical superiority.

The fortuitously timed $474 million bid reduction has led the Senate Armed Services Committee to suggest GAC's win was a buy-in. We concur. The approximately $500 million loss on the contract projected by GAC in 1972 when it threatened to refuse to perform any further production without a corresponding contract renegotiation lends credence to the buy-in interpretation.

Further substantiation is given by the manifestly unfavorable contract terms accepted -- in part proposed by -- GAC negotiators: an unprecedentedly low contract ceiling, only 125% of target cost; acceptance of a projected 2% material and 3% labor inflation rates at a time when national inflation was nearly 6%; and an inflexible, substantially fix-price contract for subsequent production lots.

GAC may have accepted such patently unfavorable contractual terms in the belief that subsequent production orders would compensate for an early loss, and because the F-14 technically was a low-risk design.

GAC had considerable experience with the F-111B and before that, with the XF-10F, the first U.S. swing-wing fighter ever built. The swing-wing design, the use of titanium, and the turbofan engine all drew upon Grumman's F-111B experience. The Phoenix/AWG-9 weapon system had been under development for almost a decade, also as part of the F-111B. There was little chance of technical failure in the F-14 such as plagued the F-111B, except for the entirely new so-called "B" engine, which did produce trouble. Indeed, actual experience substantiates that belief. The F-14 development has proceeded substantially free of such technical difficulties, except for the "B" engine.

However, GAC apparently did not provide for other less serious, if more numerous R&D phase overruns, which are typical in the development of an expensive new weapon system. The General Accounting Office has found from analysis of historical data that all such weapon systems encounter an average 30% overrun in the R&D phase. In the case of the F-14, the overrun amounted to 28% (for comparison, the F-4 figure was 25%). Congress did not appropriate extra R&D funds or approve the full 722 aircraft proposed by the Navy. As a result, the F-14

R&D budget grew at the expense of production. Fewer airplanes were planned to be built, and the program unit cost grew correspondingly from an original $13.1 million estimate to the current $16.8 million figure.

GAC attributes the F-14 cost growth to three factors: inflation, accounting for 28% of the total growth; increased overhead charges due to business base reduction, 40%; and contractor initiated engineering changes, 32%. Thus, the overruns were not primarily technical problems, but reflected the then current aerospace industry-wide depression. However, they all occurred during the R&D phase of the contract, and resulted in shifting funds from production to R&D.

The effect of total production on unit price is generally expressed by the so-called learning curve. Typically, a doubling in production reduces the unit cost of the last airplane produced by 20%. If the F-14 production were doubled from its planned 313, its program unit cost would be reduced to that of the Air Force F-15, which has a planned production run of greater than 700. This fact alone indicates that, even for all its technical sophistication, the F-14 is really no more expensive than can be expected of similar modern fighter planes. Consideration should be given by DoD to replacing the F-15 with the F-14.

The F-14 cost is not out of line with the history of the costs of fighter airplanes. This is seen by plotting fly-away fighter costs as a function of initial production year (c.f. Fig. 6.4). A statistical regression analysis of that data shows that historical fighter plane costs display an average 13% annual growth. Analysis of the annual Consumer Price Indices, developed by the Bureau of Labor Statistics, demonstrates that the average annual rate of economic inflation is 3%. Consequently, the cost of fighter airplanes has been growing at an annual average rate of approximately 10%, and the F-14 cost is not out of line historically.

The problem, then, is to explain the high F-14 unit cost itself. One approach to that explanation is to devise a cost-effectiveness comparison of the F-14 and the F-4, the plane it was designed to replace. If it can be shown that the higher F-14 unit cost is accompanied by an effectiveness such that the ratio of the two is greater than or equal to the cost-effectiveness of the F-4, then the cost of the F-14 is justified. This is not an easy calculation. A new approach is devised which offers such explanation on the assumption that the Phoenix/AWG-9 missile system performs satisfactorily.

By an extension of the classic Lanchester equations, it can be shown that if two forces of fighter aircraft are of equal fighting strength <u>and</u> of equal cost, then the ratio of the individual aircraft fighting capabilities must equal the square of their unit costs. Thus, if the F-14 costs 2½ times as much as the F-4, then the F-14 individual fighting strength must be somewhat more than 6 times that of the F-4. If the two aircraft are assumed capable of carrying the same weapons, except for the Phoenix missile, and if for sake of argument, the F-14 and F-4 are, for the moment, considered of comparable aerodynamic capability, then the cost of the F-14 is marginally justified by its six Phoenix missiles. If the latter operate nearly perfectly, then in an engagement, a single F-14 could launch the missiles and destroy an opposing force of six F-4's before the latter ever got within range of their weapons.

Obviously, the foregoing argument is highly simplified. The F-14 is aerodynamically superior to the F-4, but the Phoenix missile in an actual engagement would not have unit kill probability, especially in the presence of countermeasures. A careful and sophisticated cost-effectiveness study is required for satisfactory justification, but the preceding simplified approach lends credence to the belief that the F-14 unit cost vis-a-vis the F-4 can be explained on the basis of its performance as a sophisticated weapon system in conjunction with the Phoenix missile.

BIBLIOGRAPHY

Aerospace Daily: 22 February 1972; 13 March 1972; 16 March 1972; 1 March 1972.

Aerospace International, "How the Phantom II Got That Way," November 1966, p. 16 et seq.

Armed Forces Journal, 22 November 1969, "Is There a Case for Prototype Competition?"

Alexander, A. J., "R&D in Soviet Aviation," Rand Report R-589-PR, November 1970.

Armed Forces Journal, 14 March 1970, Letter to the Editor by G. A. Spangenberg.

Astronautics and Aeronautics, "RMV's in Aerial Warfare, W. B. Graham, p. 36 et. seq., May 1972.

Aviation Week:
6 December 1971, Letter to the Editor
20 December 1971, "Telemetry System May Cut F-14 Test Time."
20 December 1971, "Accelerated Testing Set for F-14A."
10 January 1972, Letter to the Editor
31 January 1972, Letter to the Editor
21 February 1972, "F-14 Avionics Countermeasures."
21 February 1972, "Boron Purchase."
28 February 1972, Letter to the Editor
6 March 1972, Editorial
20 March 1972, Editorial
27 March 1972, Letter to the Editor
3 April 1972, "Navy Urges Full F-14 Funding."
3 April 1972, Letter to the Editor
10 April 1972, "F-14 Subcontractors Forecase Profit under Current Program."
24 April 1972, "F-14 Funding with Restraints Urged."
24 April 1972, Letter to the Editor.

Barkey, H. D., "Evolution of the F-4 Phantom," American Institute of Industrial Engineering, Washington, D.C., 19-21 April 1971.

Christian Science Monitor, 12 November 1971.

Committee on Armed Services Report No. 92-359, 7 September 1971.

Congressional Record: Senate, 23 September 1971
Senate, S-14250, 14 December 1971
Senate, S-6844, 27 April 1972
Senate, Report No. 92-962, Committee on Armed Services, 14 July 1972,
Senate, S-3108 Hearings, Part 6, March - April 1972.
House, Hearings on 1971 DoD Appropriations, Part 7.
Senate, Committee on Armed Services, S-939, Part V, 1971.

Defense Industry Report, 20 March 1972.

GAO Report, "Evaluation of Two Proposed Methods of Enhancing Competition in Weapon Systems Procurement," B-39995, 14 July 1969.

GAO Report B-168664, "Review of F-14 Aircraft," 3 September 1971.

GAO Staff Study, "The F-14 Aircraft," Department of the Navy, March 1972.

Grumman Aircraft Corporation, "F-14A Tomcat," October 1971.

Interavia, "The Development of the McDonnell Phantom."

Jane's All the World's Aircraft, 1972, Descriptions of F-14, F-4, and Mikoyan MIG-23 (Foxbat).

Lanchester, F. W., Aircraft in Warfare, New York, Appleton, 1917.

Levenson, G. S., and Barro, S. M., "Cost-Estimating Relationships for Aircraft Airframes," RAND RM-4845PR (Abridged) May 1966.

Life Magazine, 25 September 1970.

McDonnell Douglas Corporation Report NDCA 1125, "The Phantom II," 1 June 1971.

McDonnell Douglas Corporation, Project Master Plan for F-4J Weapon System, 29 January 1971.

NSIA, Proceedings of Seminar on Prototyping, 23-24 February 1972.

Ordnance, "Major Defense Systems Acquisition," p. 198, November-December 1971.

Proxmire, Senator W., Press Release, 29 May 1972.

"Report of the Commission on Government Procurement," December 1972, U.S. Government Printing Office, Washington, D.C.

"Report to the President and Secretary of Defense on the Department of Defense," Blue Ribbon Defense Panel, 1 July 1970.

Sanchez, L. R., and Del Rossi, J. A., "Methods of Estimating Fixed-Wing Airframe Costs," Vol. I, PRCR-547A, April 1967.

Science, "Navy F-14: New Fighter's Cost, Sophistication Stir Controversy," 7 April 1972.

Spangenberg, G. A., Address, 23 January 1970.

Spangenberg, G. A., Memorandum for DSB Avionics Panel, 10 September 1971.

Statement by Senator William Proxmire, 16 April 1972.

Wall Street Journal: 27 December 1971; 11 January 1972; 30 April 1972; 30 May 1972

Washington Post: 8 November 1971; 4 December 1971; 23 January 1972; 27 January 1972; 17 April 1972; 30 April 1972.

```
SYSTEM--BASIC
NEW OR OLD--OLD
OLD FILE NAME--MULFIT***
READY.

0 DATA 18,2,1
100 DATA 54,48,53,57,55,60,60,59,66,55,50,56
101 DATA 56,70,65,72,73,64
200 DATA .45,.30,.65,1.8,1.1,1.3,2.5,.75,5.4,1.1
201 DATA .49,.45,.95,9.8,3.6,9.4,7.5,1.7
1000 LET Y = LOG (V(2))
1001 LET X(1) = V(1)
RUN

MULFIS   9:10   04 WED 08/09/72

VERSION OF 09/03/1968
```

VARIABLE	REGR COEFF	MEAN VALUE	STD DEV
0	-7.94917	.447201	1.09304
1	.140853	59.6111	7.30946

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE
TOTAL	17	20.4968	1.2057
REGRESSION	1	18.0197	18.0197
ERROR	16	2.47706	.154816

INDEX OF DETERMINATION: .879143

F-RATIO TEST STATISTIC: 116.393

ACTUAL	CALCULATED	DIFFERENCE	PCT DIFFER
-.798508	-.343133	.455369	-132.7
-1.20397	-1.18825	1.57193E-02	-1.3
-.415515	-.483991	-6.84755E-02	14.1
.587787	7.94191E-02	-.508368	-640.1
9.53102E-02	-.202286	-.297596	147.1
.587787	.501977	-.08581	-17
.916291	.501977	-.414314	-82.5
-.287682	.351124	.638806	179.6
1.6864	1.34709	-.339307	-25.1
9.53102E-02	-.202286	-.297596	147.1
-.71335	[illegible]	-.175175	21.3
-.798508	-6.14334E-02	.737074	-1199.7
-5.12733E-02	-6.14334E-02	-1.01411E-02	19.5
2.28238	1.9105	-.371331	-19.4
1.22378	1.14904	-7.47744E-02	-6.1
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
.530628	1.06539	.534759	50.1

END

DATE
FILMED

6-73